EXHIBIT 22

UNITED STATES DISTRICT COURT
FOR THE DISTRICT OF NEW HAMPSHIRE

OCADO INNOVATION LTD. and OCADO SOLUTIONS LTD., Plaintiffs, v. AUTOSTORE AS and AUTOSTORE SYSTEM INC., Defendants.	)	Case No. 1:21-cv-00041 **JURY TRIAL DEMANDED**

<u>DECLARATION OF PROFESSOR RAFFAELLO D'ANDREA</u>

I, Raffaello D'Andrea, Ph.D., declare as follows:

1. I submit this declaration at the request of plaintiffs Ocado Innovation Ltd. and Ocado Solutions Ltd. to provide my opinions as to whether the claims of U.S. Patent No. 10,901,404 (the "'404 Patent") are directed to patentable subject matter under 35 U.S.C. § 101. This report contains statements of the opinions I have formed to date, and the technical and other reasons and bases for those opinions. I may offer additional opinions based on further review of materials in this case, include the opinions and/or testimony of other expert witnesses. I make this declaration based upon my own personal knowledge and, if called upon to testify, would testify competently to the matters set forth herein.

2. In summary, my opinions are as follows:

- The claims of the '404 Patent are directed to patentable subject matter under both steps 1 and 2 of the *Alice* test as it has been explained to me.
  - As to step 1, the claims of the '404 Patent are not directed to an abstract idea. The claimed inventions provide a technological solution to a set of problems that specifically arise in the context of stacked-bin grid storage

systems (as described below), and are directed to technology and operations that cannot be performed in the human mind.

- As to step 2, the claims of the ’404 Patent include inventive steps that were not well known, conventional or routine activity at the time the patent was filed in 2014. At least two elements of the independent claims, the reservation unit and the clearance unit, were not used in prior systems in the manner described and claimed in the ’404 Patent. The same is true of other elements set out in the dependent claims.

I. Background and Qualifications

3. I am a citizen of Canada currently residing in Wollerau, Switzerland, where I am a Professor of Dynamic Systems and Control at ETH Zurich. I have more than 30 years of experience in developing robots and the control systems that allow robots to interact and coordinate to perform tasks.

4. I received a Bachelor of Science degree from the University of Toronto in Engineering Science in 1991, and a Master of Science in Electrical Engineering from the California Institute of Technology in 1992. After receiving my Ph.D. in Electrical Engineering from the California Institute of Technology in 1997, I became an assistant professor in mechanical and aerospace engineering at Cornell University. In 2003, I was promoted to associate professor at Cornell University. My research at Cornell was directed to the design and control of autonomous, multi-agent and multi-robot systems. Since 2007, I have been a full professor at ETH Zurich, where my research is directed to the same.

5. In 2003, while on sabbatical from Cornell, I co-founded Kiva Systems (“Kiva”)—now Amazon Robotics—a company that designs and manufactures robotic order fulfillment systems for use in warehouses. I served as the Chief Technical Advisor for Kiva from 2007—when I joined ETH Zurich as full professor—until 2012. In addition to my current position at ETH Zurich, I also founded and serve as CEO for a robotics company, Verity AG, and co-founded and serve as advisor for an index, advisory and research company, Robo Global

Investments and Exchange Traded Funds, which is focused on robotics, artificial intelligence and healthcare technologies.

6. At Kiva, I directed the mechatronic design and development of robots and their control software for materials handling applications, specifically for use in retail order fulfillment applications. Perhaps more relevant here, I was also responsible for designing and implementing software solutions to coordinate the movement of large numbers (dozens to hundreds) of robots on the "virtual" grid system used in the Kiva warehouse. My work in this area led to numerous patents around the world including, for example, U.S. Patent No. 7,912,574, which describes the robot movement system we developed and implemented.

7. Based on my experience, I have personal knowledge of and am intimately familiar with the use and coordination of robots in warehouse environments, as the technology has developed. This includes the technology to which the '404 Patent is directed.

8. I have received numerous awards for my work and research in the field of robotics, as listed in my CV attached hereto as Appendix A. For example, I received the IEEE-IFR Invention and Entrepreneurship Award in Robotics and Automation from the Institute of Electrical and Electronics Engineers in 2008 for my work at Kiva, and was named an IEEE fellow in 2010. I have received the Engelberger Robotics Award (2015) and the IEEE Robotics and Automation Award (2016), the two most prestigious awards in the robotics community. I was inducted in the U.S. National Inventors Hall of Fame in 2020 for my work at Kiva, and specifically for my inventions directed to "Mobile Robotic Material Handling for Order Fulfillment." I was subsequently elected to the U.S. National Academy of Engineering in 2020 in recognition of my "contributions to the design and implementation of distributed automation systems for commercial applications."

9. I am the author of hundreds of peer-reviewed publications, and numerous presentations, in the field of robotics and control systems. A complete list of my publications is provided in the download from Google Scholar attached as Appendix B. Among other relevant publications, I am a co-author, with P.R. Wurman and M. Mountz, of the article "Coordinating Hundreds of Cooperative, Autonomous Vehicles in Warehouses," published in AI magazine in 2008; this article describes the system we developed at Kiva.

10. I am named as an inventor in numerous patents around the world, including several dozen in the United States.

11. I previously provided an expert report and deposition on behalf of Parrot Group in the U.S. Patent and Trademark Office *inter partes* review IPR2014-00732 (U.S. Patent No. 8,106,748). I have not provided testimony as an expert witness in any other litigation or proceeding.

12. I have been retained as an expert witness by Plaintiffs, who are being charged at my hourly rate of CHF1250 for my consulting services. My compensation in no way depends on the outcome of this proceeding or the content of my testimony.

13. In forming my opinions, I have reviewed and considered the materials cited in this declaration, including the following:

- U.S. Patent No. 10,901,404
- Prosecution History of App. No. 15/992,899
- Prosecution History of App. No. 16/575,906

II. Relevant Legal Standards

14. I am not a lawyer. I have been informed by attorneys of the following relevant legal principles and have applied them to arrive at the opinions set forth in this declaration.

15. I understand that the Supreme Court, in *Alice Corporation* v. *CLS Bank International*, 573 U.S. 208 (2014), established a two-step test to determine if claims are directed to patentable subject matter. In the first step, one determines whether the claims are directed to an abstract idea or other patent-ineligible concept. If so, second step asks whether the claims contain an inventive concept that transforms the abstract idea into something patent-eligible; such an inventive concept must be more than a general instruction to apply an abstract idea, and more than just well understood, routine or conventional activity previously known to the industry.

16. In applying the *Alice* test for patentable subject matter, I understand that the claims are to be interpreted as they would be understood by one of skill in the art, in light of the claim language itself, as well as the description of the invention in the patent specification and drawings, and its prosecution history. In reaching the opinions set out in this declaration, I have interpreted the claims in this way, although given the limited nature of my assignment I have not attempted to formally construe each claim element that may be disputed by the parties in this litigation. In my opinion, a person of ordinary skill in the art to which the '404 Patent is directed would have a B.S. degree in Electrical Engineering, Computer Science, Mechanical Engineering, Robotics or a related field, and three to five years of experience in the design or operation of robot control systems, or an M.S. degree in one of these fields, or a related field, and one to three years of experience.

III. The Inventions Claimed in the '404 Patent

17. ***Introduction.*** The inventions claimed in the '404 Patent are directed to the coordination of automated warehouse storage systems for businesses selling multiple product lines. '404 Patent, at 1:27-29. Certain businesses, such as grocery stores or other retail operations, may need to store tens or even hundreds of thousands of different products in the

warehouse, and the success of such businesses is highly dependent on their ability to organize, retrieve and return items to the storage system. The ’404 Patent claims systems and methods for “controlling movement of transporting devices arranged to transport containers stored in stacks arranged in a facility having pathways arranged in a grid-like structure above the stacks, the transporting devices being configured to operate on the grid-like structure.” ’404 Patent, Abstract.

18. The patent explains that prior warehouse storage systems typically consisted of storage bins or storage containers that hold the products sold by the business. *Id.* at 1:30-34. The storage containers are arranged on rows of shelves with aisles between the rows of shelves. *Id.* The aisles in the prior systems provide access to the shelves, so that the products in the storage containers can be retrieved by human operatives or robots traveling in the aisles. *Id.* at 1:34-36.

19. Because of the need to provide substantial aisle space, the storage density of such prior systems may be relatively low, meaning that a great deal of aisle space must be provided to gain access to a relatively small amount of shelf storage space. *Id.* at 1:37-42.

20. In recent years, however, a warehouse configuration has been developed that eliminates the aisles between the shelves. Instead of being arranged on shelves separated by aisles, the storage containers, or bins, are stacked on top of one another in columns and the stacks are arranged in rows. *Id.* at 1:50-52. The containers can then be accessed by robotic vehicles operating on an X/Y grid that provides pathways to access each column *from above*. *Id*. at 1:56-62. Such storage systems allow many more containers to be stored in a given volume or area. *Id*. at 1:52-55.

21. However, the use of such stacked-bin grid storage systems creates unique problems that are addressed by the controller described and claimed in the '404 Patent:

- Humans themselves cannot move effectively on the grid, or efficiently retrieve bins from the stack. Thus, robotic vehicles, and not human operatives, must be directed and coordinated to use the system.
- In order to achieve the throughput necessary to fulfill orders efficiently in a retail storage environment that may provide thousands of different products, the simultaneous operation and coordination of hundreds of robots on the grid may be required. In addition, because of the dense configuration of the grid, and the wide use of metal grid columns and other structures that interfere with radio communications, the likelihood of missed or dropped communications between the controller and the robots is substantially increased.
- The starting points and destinations for the robotic vehicles are constantly changing as different products are retrieved and delivered. As a result, the pathway each robot must use is constantly changing as the robot is assigned new tasks.
- While the pathways used by the robots are constantly changing, the number of potential discrete routes from any starting point to any destination on the grid is limited by the grid structure, which does not allow robots to, for example, turn off the grid to get out of the path of another robot. The paths executed by each robot must be coordinated, in real time, to ensure that the robots do not collide.
- Robots do not behave ideally or act precisely according to models of their behavior. They may move more slowly or quickly than anticipated due to loading or other issues, or they may break down. Because of this, it is impossible to precisely anticipate the future location of every robot in the system in order to avoid collisions as robot behavior deviates from the ideal.

Because of these issues, as the '404 Patent explains, "[t]he co-ordination of the movement of the one or more robotic or otherwise automated means may be an important consideration in determining the overall efficiency and scalability of a system for storage and retrieval of a large number of different products." *Id.* at 1:63-67.

22. The problem facing the inventors of the '404 Patent, in essence, was the near-simultaneous determination of multiple, high-performance, collision-free paths for hundreds of

robots in real time. At the time the first application that led to the '404 Patent was filed in mid-2014, the coordinated path planning for a multitude of autonomous vehicles had only recently become the object of serious study. Even then, most work at that time focused on decentralized path planning (such as for an autonomous car), not on centralized, high-performance path planning for hundreds of robots or vehicles acting in a coordinated fashion.

23. At the time of the inventions claimed in the '404 Patent, it was recognized that any solution to the problem involved a trade-off between the system throughput required for operation, on the one hand, and the ability of existing computer systems to perform the required path-planning and dynamic optimization (in the context of the movement of other robots and the resulting communication requirements) in real time. As a result, the systems that were proposed generally did not plan and coordinate conflict-free paths for each robot from starting point to destination. Instead, the prior art control systems simply planned a route from start to finish *without taking account of the movements of other robots on the grid*, and relied on other means—such as proximity sensors on the robots themselves—to ensure there were no collisions, at the expense of system performance. Such collision avoidance systems (*e.g.*, proximity sensors), although potentially adequate in a system with low vehicle density, were not adequate to address the problems raised by stacked-bin grid storage systems. In that context, as the density of robots on the grid increases to meet throughput requirements, the likelihood of a collision becomes significantly greater if a robot's planned path does not take into account the planned paths of the other robots. With the increased probability of collision, it is inefficient to rely on, *e.g.*, *ad hoc* proximity sensors as the collision avoidance mechanism.

24. ***Claim 1—The Movement Optimization, Reservation and Clearance Units.*** Claim 1 of the ’404 Patent sets out one solution by the inventors to the problems created by the use of automated stacked-bin grid storage systems. It claims:

> 1. A system for controlling movement of transporting devices arranged to transport containers, the containers being stored in stacks arranged in a facility, the facility having pathways arranged in a grid-like structure above the stacks, the transporting devices being configured to operate on the grid-like structure, the system comprising:
>
>> a movement optimisation unit configured to determine a route of a transporting device from one location on a grid-like structure to another location on the grid-like structure for each transporting device;
>>
>> a reservation unit configured to reserve a path on the grid-like structure for each transporting device based on the determined route, wherein the path reserved for each transporting device is provided such that no two transporting devices have locations on the grid-like structure which would cause transporting devices to overlap at a same time; and
>>
>> a clearance unit configured to provide a clearance instruction for each transporting device to traverse a portion of the reserved path,
>>
>>> wherein the clearance instruction is provided for execution by a control unit on each transporting device at a future time.

25. The invention of the ’404 Patent addresses the problems created by the use of stacked-bin grid storage systems by creating a three-component system to coordinate the simultaneous movement of hundreds of robots on a grid.

26. First, as in prior systems, a movement optimization unit is used to determine a “route” from one location to another location—a series of movements and turns that will take a robot from a starting point to a destination. The routes identified by the movement optimization unit are time-independent, however, and do not take into account the movements of other robots on the grid. As such, any particular route may have the potential for collisions between robots. *See generally* Response to Office Action in App. No. 15/992,899, dated Dec. 3, 2018, at 2-3 (attached as Appendix D).

27. The next component, however, was not used in prior systems. The ’404 Patent claims the use of a reservation unit to select and “reserve,” from among a set of the time-independent routes created by the movement optimization unit for a particular robot, a path from the starting point to the destination such that “no two transporting devices have locations on the grid-like structure which would cause transporting devices to overlap at a same time.” ’404 Patent, at claim 1. The ’404 Patent explains that, to do this, the reservation unit uses a model of robot behavior to determine *when* the robot will traverse each portion of the route. It compares this to the reserved paths already stored for other robots, to determine whether a particular route will require the robot to traverse a part of the route at the same time that part of the route is expected to be traversed by another robot. If there is any overlap in both space and time, the path cannot be reserved for the robot, and the reservation unit evaluates another route. *See* ’404 Patent at 19:30-50; Response to Office Action in App. No. 15/992,899, dated Dec. 3, 2018, at 3. The reservation is thus “designed to create non-conflicting robot movement plans.” ’404 Patent at 19:34-35.

28. As discussed above, the use of a reservation unit in this way was unconventional and not well understood at the time of the invention claimed in the ’404 Patent. Control systems did not plan/reserve non-conflicting routes, from starting point to destination, that took into account the previously planned and reserved paths for each of the other robots in the system. The ability of the invention claimed in the ’404 Patent to reserve non-conflicting paths through upfront processing and preplanning in this way substantially reduces, the possibility of robot collisions in highly dense systems. As a result, the performance of the system is increased because other, less efficient collision avoidance systems (including, for example, robot proximity sensor systems) are invoked much more rarely.

29. As its third component, the invention claimed in the '404 Patent includes a clearance unit to provide a robot on a reserved path with permission to traverse the next portion of the path. The clearance module grants permission to "to traverse a *portion* of the reserved path" (*i.e.*, a portion of the path reserved by the reservation unit) only after "check[ing] that it will not be possible to collide with another robot," based on, among other things "the current positions and speeds of robots." '404 Patent, claim 1 (emphasis added); *id.* at 18:38-45; *see also id.* claim 8. In other words, the clearance unit monitors and uses the actual behavior of the robot on the grid to predict potential collisions; the unit denies clearance to traverse a section of the path if it predicts a collision may occur if clearance were granted.

30. The clearance unit accounts for the fact that the use of a movement optimization unit and a reservation unit, by themselves, may not result in perfectly non-conflicting paths because the robots may not exactly follow the planned time course. Robots may become marginally off-path due to non-ideal robot behavior as a result of, among other things, missed communications, sync errors, or discrepancies between actual robot behavior and the model used to plan and reserve the path. '404 Patent, at 18:64-67. The clearance unit thus is used to issue permissions for a robot to continue along a portion of a reserved path if no collision is predicted to occur in light of the actual running behavior of the robot. *See, e.g.*, '404 Patent, claim 11 (clearance unit configured to provide clearance instruction "based upon . . . [robot] discrepancies with a physics model" of robot behavior); claim 12 (entry points provided by clearance unit based on "[robot] position [or] speed updates"). Because the clearance unit relies on predictions based on the actual behavior of the robot, clearance instructions may—so long as significant deviations from model behavior are not observed—be provided in advance, "for execution [by the robot] at a future time," as required by claim 1.

31. A clearance unit as claimed in claim 1 of the ’404 Patent was not, to my knowledge, used in prior systems, and its use in claim 1 was unconventional and not well understood at the time of the invention. Earlier systems either did not provide clearance to traverse a portion of a planned route (but merely instructed the robot to turn or stop to prevent an imminent collision), or did not provide clearance based on the potential for collisions based on the actual behavior of the robot. For example, the Kiva control system that is the subject of my U.S. Patent No. 7,912,574 (’574 Patent) included a limited clearance system (described as a “reservation module” in the patent) that did not provide clearance based on predicted robot behavior, but simply checked if another robot had already been cleared to traverse a relevant portion of the path. *See* ’574 Patent, at 18:13-15 (“[S]egment reservation module determines [whether a robot can reserve a particular segment of a path] based solely on whether another [robot] currently has the requested segment reserved.”).

32. If the clearance unit predicts a collision, clearance is denied and a new path can be planned and reserved “dynamically”—at the time clearance is refused—for the non-cleared robot. This is set out in, for example, dependent claims 5 and 9 of the ’404 Patent. This dynamic re-planning is a key inventive feature of the ’404 Patent, and it likewise was not a feature of prior systems. Prior art systems simply commanded the robot to turn or stop to avoid a potential collision.

33. ***Claim 1 of the ’404 Patent Is Not Directed to an Abstract Idea.*** I understand that, at step 1 of the *Alice* test for patentable subject matter, the question is whether the claims are directed to an abstract idea. In my opinion, the claims of the ’404 Patent (including claim 1) are not directed to an abstract idea, but rather to a technological solution to a problem that arises primarily in the context of the use of stacked-bin grid storage systems. As I discussed above, the

transition to a stacked-bin grid storage system required systems that were able to coordinate hundreds of robots, in real time, where the robots are constrained to use a limited number of discrete routes, substantially increasing the possibility of a collision. The paths used by the system must be optimized (to provide the throughput required for retail operations) but must at the same time account for the possibility of missed-communications and non-ideal robot behavior.

34. The system claimed in claim 1 of the '404 Patent provides a technological solution to this problem that provides an improvement in controller technology as compared to prior systems. The use of a movement optimization unit in combination with a reservation unit provides each robot with an optimized path to accomplish the task that has been assigned to that robot. The reservation unit, by taking into account the reserved movements of other robots, ensures that the robot can almost always traverse the reserved path without colliding with another robot. This pre-processing substantially reduces the risk of a collision. Finally, the clearance system monitors and uses the actual behavior of the robot to eliminate any remaining potential for collisions that could arise as a result of non-ideal robot behavior, while (through re-planning) ensuring that the robot stays on a reserved, non-conflicting path.

35. I understand that AutoStore contends that claim 1 is directed to the abstract idea of "vehicle routing." In my opinion, AutoStore has abstracted away the individual elements of the claim, which provide a particular solution to the particular vehicle routing problems raised by a stacked-bin grid storage system. As I discussed above, at the time of the invention claimed in the '404 Patent, coordinated path planning for a multitude of autonomous vehicles had only recently become the object of serious study, and little, if any, focused on centralized, high-performance path planning for the coordination densely packed robots moving in a grid storage

system. To my knowledge, of the limited work that had been done in this area, none combined a movement optimization unit, reservation unit and clearance unit as claimed in the '404 Patent, or used a reservation unit or clearance unit in the manner described and claimed in the patent. This was confirmed by the examiner of the '404 Patent, who found that the limitations of claim 1 "alone and in combination with the other limitations in the independent and dependent claims, were neither found, nor taught or fairly suggested, in the prior art of record." Notice of Allowance in App. No. 16/575,906, dated Nov. 5, 2020, at 2-3 (attached as Appendix E).

36. I understand that AutoStore also contends that the claims of the '404 Patent are directed to an abstract idea because, it contends, they could be carried out mentally or with the aid of pen and paper. In my opinion, this is ridiculous. Humans simply cannot carry out the movement planning and path optimization processes as necessary to provide collision-free paths as the robots carry out their assigned tasks at the speeds required to coordinate hundreds of robots simultaneously and in real time.

37. Moreover, the system claimed in the '404 Patent is inextricably tied to the management of *robots*, which requires the controller to have capabilities humans do not have, including the ability to receiving electronic status reports from the robots, to electronically track the location and movement of each robot, and to communicate electronically with the robots to provide predetermined paths and clearance commands.

38. ***The Claims of the '404 Patent Include Inventive Concepts.*** I understand that, at step 2 of the *Alice* analysis, the question is whether the claims include one or more inventive concepts sufficient to transform a claimed abstract idea into a patent-eligible claim. I understand that the required inventive concepts add limitations that are not well understood, routine or conventional activity.

39. *Independent Claims 1, 20, Dependent Claims 15 and 16.* As explained above, in my opinion claim 1 of the '404 Patent includes at least two inventive concepts that were not well understood, routine or conventional activity. The use of a reservation unit to reserve, in real time, a time-dependent and collision-free path from the robot's starting point to its destination, taking into account the previously reserved paths of all of the other robots in the system, simply was not used in prior systems, much less "routine[ly]" used. *See supra* ¶¶ 27-28. The ability of the invention claimed in the '404 Patent to reserve paths in that non-conventional way dramatically reduced the possibility of robot collisions, and required less reliance on other, less efficient, collision avoidance systems. *Id.* ¶ 28. This in turn allowed the clearance system (discussed below) to be more tolerant of non-ideal robot behavior and missed communications. The use of such a reservation unit certainly was not well understood or conventional. Independent claim 20 simply claims the method used by the controller of claim 1, dependent claim 15 claims the storage system including the controller of claim 1 and claim 16 claims the storage system of claim 15 in which the robot covers a single grid space. Each of these claims is directed to patentable subject matter for the same reasons as claim 1.

40. Likewise, a clearance unit as claimed in claim 1 was not well understood, routine or conventional. Unlike the system of claim 1, prior and contemporaneous systems did not monitor and use the actual behavior of the robot on the grid to predict potential collisions, and to deny clearance to traverse a section of an already reserved path when the clearance unit predicts that a collision may occur in the future if clearance were to be granted. *See supra* ¶¶ 29-31. Nor did prior systems provide clearance commands for execution by the robot to traverse a portion of a reserved path at a future time, as required by claim 1. Prior systems either did not include a

clearance system, or did not use predictions of future robot behavior to generate clearance commands. *See supra* ¶ 31.

41. *Dependent Claim 2.* Claim 2 provides that the interval between the time the clearance instruction is provided and the time it is executed by the robot "is a configurable parameter." Because the use of a clearance unit was not well understood, routine or conventional at the time of the invention, neither were the elements of claim 2.

42. *Dependent Claims 3-4, 6, 10.* These claims are directed to withholding of clearance by the clearance unit in the event of a communications failure between the controller and the robot. *See* '404 Patent, claim 3 (clearance instruction not provided "until a last issued clearance instruction is acknowledged" by the robot); claim 4 (clearance unit configured to "cancel an existing reserved path" when "the last issued clearance instruction is not acknowledged" within set time); claim 6 (system grants or withholds clearance "in response to a status report received" from each robot); claim 10 (system re-plans "when at least one message is not received by the system" from the robot). Because the use of a clearance unit was not well understood, routine or conventional at the time of the invention, neither were the elements of these claims. In addition, the elements added by these claims were not routine or conventional at the time of the invention because they addressed a problem—the increased likelihood of missed communications between the robot and the controller—that became critically important only in the context of stacked-bin grid warehouse configurations. *See supra* ¶ 23.

43. *Dependent Claims 5, 9.* These claims are directed to an important inventive feature, which is dynamically re-planning the path to be taken by the robot when communications are lost or clearance is denied. *See* '404 Patent, claim 5 (system of claim 1 "configured to re-plan" when "communication is re-established" with the robot); claim 9 (system

of claim 1, where clearance and/or optimization units are "configured to dynamically re-plan"). These claims are directed to the steps used by the controller to keep the robot on a reserved, non-conflicting route at all times. The elements added by these claims were not well understood, routine or conventional at the time of the invention because prior systems simply directed a robot to change its motion upon detecting an imminent collision between two robots, but did not attempt to keep each robot on a reserved path to minimize the possibility of collisions with *other* robots. *See supra* ¶ 32.

44. *Dependent Claims 7, 8, 11-14.* These claims are directed to refinements of the basic clearance unit. *See* '404 Patent, claim 7 (clearance unit "configured as a passive collision avoidance system"); claim 8 (clearance unit configured to grant or withhold clearance based on identified parameters, including robot speed and position); claim 11 (clearance unit configured to provide clearance based on listed parameters, including discrepancies with a physics model); claim 12 (clearance unit configured to provide "safe entry times" for a position on the grid based on listed parameters including robot position and/or speed updates); claim 13 (clearance unit configured to provide clearance instructions for a predetermined period of time); claim 14 (clearance unit configured to provide various types of notifications to the control unit). Because the clearance unit as claimed in claim 1 of the '404 Patent was itself not well understood, routine or conventional, the additional elements further defining the clearance unit were likewise neither routine nor conventional.

45. *Dependent Claims 17-19.* These dependent claims are directed to a storage system using the controller of claim 1, in which the robot or clearance unit is configured to take particular actions when a clearance instruction is received too late by the robot. *See* '404 Patent, claim 17 (robot configure to "ignore" a clearance instruction that "is not received before a

scheduled start time"); claim 18 (robot configured to return a "received too late" status message when clearance instruction "is not received before a scheduled start time"); claim 19 (clearance unit configured to cancel reservation and re-plan a path when "the clearance instruction was received too late" by the robot). Because the clearance unit as claimed in claim 1 of the '404 Patent was itself not well understood, routine or conventional, the additional elements of defining actions to be taken when the clearance instruction is sent or received too late were likewise neither routine nor conventional.

I declare under penalty of perjury under the laws of the United States of America that the foregoing is true and correct.

Executed on April 23, 2021 at Wollerau, Switzerland

Raffaello D'Andrea

APPENDIX A

RAFFAELLO D'ANDREA[1]

www.raffaello.name

APPOINTMENTS

Founder, CEO, and chairman of the board, Verity AG. **Since 2014.**
Co-founder and advisor, Robo Global Investments and Exchange Traded Funds. **Since 2013.**
Chief technical advisor, Kiva Systems. 2008-2012.
Professor of dynamic systems and control, ETH Zurich. **Since 2008.**
Co-founder and co-CTO, Kiva Systems. 2003-2007.
Associate professor, mechanical and aerospace engineering, Cornell University. 2003 - 2007 (on leave).
Assistant professor, mechanical and aerospace engineering, Cornell University. 1997 - 2003.

EDUCATION

Ph.D., California Institute of Technology, Electrical Engineering. 1997.
M.S., California Institute of Technology, Electrical Engineering. 1992.
B.Sc., University of Toronto, Engineering Science. 1991.

SELECT HONORS AND AWARDS

National Academy of Engineering (United States of America). 2020.
National Inventors Hall of Fame (United States of America). 2020.
IEEE Robotics and Automation Award. 2016.
Engelberger Robotics Award. 2015.
Best Paper Award, IFAC Mechatronics Journal. 2014.
Best Paper Prize, IFAC World Congress. 2011.
IEEE-IFR Invention and Entrepreneurship Award in Robotics and Automation. 2008.
Excellence in Teaching Award, Cornell College of Engineering. 2005.
RoboCup World Champions, F180 League, Systems Architect and Faculty Advisor. Padova, Italy. 2003.
RoboCup World Champions, F180 League, Systems Architect and Faculty Advisor. Fukuoka, Japan. 2002.
Presidential Early Career Award for Scientists and Engineers (United States of America). 2001.
RoboCup World Champions, F180 League, Systems Architect and Faculty Advisor. Melbourne, Australia. 2000.
RoboCup World Champions, F180 League, Systems Architect and Faculty Advisor. Stockholm, Sweden. 1999.
Best Student Paper Award, IEEE Conference on Decision and Control. 1996.
O. Hugo Schuck Best Paper Award, AACC American Control Conference. 1994.
Natural Sciences and Engineering Research Council of Canada 1967 Fellow. 1991-1996.
University of Toronto Wilson Medal. 1991.
Valedictorian, Anderson CVI, Whitby, Canada. 1986.

SELECT SPEAKING ENGAGEMENTS

Digitilize in Stockholm, 2020.
USI, 2019.
The Big Challenge Science Festival, 2019.
CLSA Investor Forum Hong Kong, 2019.
CLSA Investor Forum Japan, 2019.
Nyquist Lecture, Yale University, 2018.
Kelly Distinguished Lecture on Robots and Jobs, Georgia Tech, 2017.
Mediterranean Conference on Control and Automation plenary, 2017.
T-Edge Beyond The Impossible Conference, 2016.
Seoul Future Conference, 2016.
Glass Memorial Lecture Series, University of Toronto, 2016.
TED, 2016.
Indian Control Conference plenary, 2016.
LAUNCH Distinguished Lecture Series, University of Illinois, 2015.
Swiss Energy Climate Summit, 2015.
USI, 2015.
Microsoft Research Devices and Networking Summit, 2015.
DLD, 2015.
Zurich.Minds, 2014.
University California Santa Barbara "Engineering the Future" Lectureship, 2014.
Crocco Colloquium, Princeton University, 2014.
International Conference on Simulation, Modeling, and Programming for Autonomous Robots plenary, 2014.

[1] Jan 26, 2021

Canadian Conference on Computer and Robot Vision plenary, 2014.
ACM Symposium on User Interface Software and Technology plenary, 2013.
Maker Faire Rome - The European Edition, 2013.
RoboCup International Symposium plenary, 2013.
Robotics Science and Systems plenary, 2013.
TED Global, 2013.
Zurich.Minds, 2012.
Society for Design and Process Science plenary, 2012.
International Symposium on Software Engineering for Adaptive and Self-Managing Systems plenary, 2012.
IEEE International Conference on Robotics and Automation plenary, 2010.
University of Texas at Dallas Center for Values in Medicine, Science, and Technology Lecture Series, 2010.
DLD, 2009.
Dean's Distinguished Lecture Series, Faculty of Engineering, Yale University, 2008.
Tetelman Lecture, Yale University, 2008.
International Conference on Robot Communication and Coordination plenary, 2007.
Conference on Cellular Automata for Research and Industry plenary, 2006.
ideaCity, 2006.
College of Engineering Distinguished Speaker Series, Rochester Institute of Technology, 2005.
Engineering Academy of Japan International Symposium, 2004.
Robot Motion Control Conference plenary, 2004.
Air Force Rome Laboratories Information Institute's Frontiers in Information Sciences Distinguished Lecture Series, 2004.
Spoletoscienza, Spoleto Festival, 2003.
American Control Conference plenary, 2003.
SIAM Conference on Control and its Applications plenary, 2001.
Sigma Series Public Lecture and Colloquium, NASA Langley Research Center, 2001.
National Science Foundation Research Highlight Series, 2001.
IEEE Conference on Decision and Control plenary, 2000.

SELECT SHOWS, EXHIBITIONS, AND DEMONSTRATIONS

Flying Machine Design and Choreography (with Verity Studios)
- Céline Dion Courage tour. November 2019 - present.
- Beyond Limits (Guinness World Record with British Telecom), London. October 2019.
- 2047 Apologue 3, Beijing. September 2019.
- CCTV New Year's Gala, China. January 2019.
- Drake North American tour. July 2018 - July 2019.
- Starlight Express, Bochum. May 2018 - present.
- Circus Knie, Switzerland. February 2018 - July 2018.
- Knicks pre-game show, Madison Square Garden, New York. September 2017 - May 2018.
- Metallica Worldwired tour. October 2017 - October 2019.
- 2047 Apologue, Beijing. June 2017.
- Cirque du Soleil's PARAMOUR on Broadway, New York. April 2016 - April 2017.

Meet the Dazzling Flying Machines of the Future (with Verity Studios and IDSC[2])
- TED, Vancouver, Canada. February 2016.
- Zurich.Minds, Zurich, Switzerland. November 2014.

Flying Machine Arena (with IDSC)
- "Sparked", Cirque du Soleil. September 2014.
- TED Global, Edinburgh, Scotland. June 2013.
- Zurich.Minds, Zurich, Switzerland. December 2012.
- Google IO, San Francisco, USA. June 2012.
- Hannover Messe, Hannover, Germany. April 2012.

Flight Assembled Architecture (with IDSC and Gramazio & Kohler)
- FRAC Centre, Orleans, France. December 2011 - February 2012.

Balancing Cube (with Sebastian Trimpe/IDSC)
- IFAC World Congress, Milan, Italy. August 2011.
- Festival Della Scienza, Genoa, Italy. October 2009.
- Nacht der Forschung, Zurich, Switzerland. September 2009.

Blind Juggler (with Philipp Reist/IDSC)
- Exploratorium, San Francisco, USA. November 2011.
- Museum for Communication, Berlin, Germany. May - September 2010.
- Heinz Nixdorf Museum, Paderborn, Germany. November 2009 - March 2010.
- Festival Della Scienza, Genoa, Italy. October 2009.
- Robodays, Odense, Denmark. September 2009.
- Nacht der Forschung, Zurich, Switzerland. September 2009.

[2]Institute for Dynamic Systems and Control, ETH Zurich.

Robotic Chair (with Max Dean and Matt Donovan)
Cabaret Voltaire, Zurich, Switzerland. March 2009.
London Art Fair, London, England. January 2009.
National Gallery of Canada, Ottawa, Canada. October 2008 - February 2009.
Ottawa Art Gallery, Ottawa, Canada. November 2008.
Flowers Gallery, London, England. July - August 2008.
Contemporary Art Gallery, Vancouver, Canada. June - August 2008.
Yale School of Art, Yale University, New Haven, USA. January 2008.
Luminato Festival, Toronto, Canada. June 2007.
International Contemporary Art Fair of Madrid (ARCO), Spain. February 2007.
Ars Electronica, Linz, Austria. September - October 2006.
ideaCity, Toronto, Canada. June 2006.

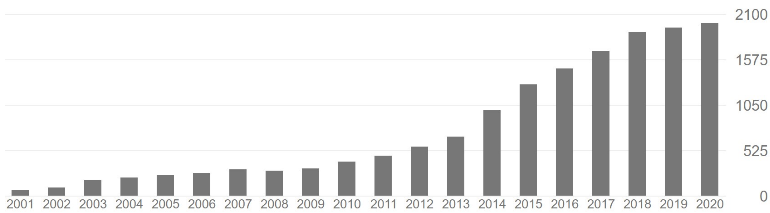
Table (with Max Dean)
National Gallery of Canada, Ottawa, Canada. October 2008 - February 2009.
National Gallery of Canada, Ottawa, Canada. October 2002 - February 2003.
Biennale di Venezia, Venice, Italy. June - October 2001.

Cornell Autonomous Robot Soccer Team
Festival dei Due Mondi, Spoleto, Italy. July 2003.
Tech Museum of Innovation (now known as The Tech Interactive), San Jose, USA. January 2001.
Smithsonian, Washington, USA. December 1999.

COLLECTIONS

Changi Airport, Singapore. Robotic Chair, 2021.
Museum Tinguely, Basel, Switzerland. Robotic Chair, 2016.
FRAC Centre, Orleans, France. Flight Assembled Architecture, 2011.
Heinz Nixdorf Museum, Paderborn, Germany. Blind Juggler, 2009.
National Gallery of Canada, Ottawa, Canada. Robotic Chair, 2006.
National Gallery of Canada, Ottawa, Canada. Table, 2003.

CITATIONS



	All	Since 2016
Citations	15985	9095
h-index	66	52
i10-index	212	152

Google Scholar, Jan 26, 2021

SELECT RESEARCH GRANTS

PRINCIPAL INVESTIGATOR

Extending the Capabilities of Small Autonomous Flying Vehicles
Swiss National Science Foundation. January 2016 - December 2019.

Approximate Model Predictive Control
ETH Independent Investigator Research Award. January 2016 - December 2018.

Distributed Estimation and Control of Mechatronic Systems
Swiss National Science Foundation. February 2014 - January 2018.

Aerial Construction
ETH Independent Investigator Research Award. September 2012 - August 2015.

Control of Underactuated Systems Composed of Subsystems with Identical Dynamics
ETH Independent Investigator Research Award. September 2011 - August 2014.

High Performance Maneuvers and Trajectory Generation for Quadrotor Flying Vehicles
Swiss National Science Foundation. October 2011 - September 2014.

Optical Motion Capture System for Robot Experiments in Real World Environments
Swiss National Science Foundation. December 2011 - November 2012.

Distributed Estimation and Control of Mechatronic Systems
Swiss National Science Foundation. November 2009 - October 2012.

Design of Robust, Networked Control Systems via Convex Optimization
US National Science Foundation. November 2003 - October 2006.

Control of Vehicle Swarms
US Air Force Office of Scientific Research, PECASE Award. May 2002 - December 2007.

Control of Spatially Interconnected Systems, with Application to Coordinated Vehicle Control
US Air Force Office of Scientific Research. October 2000 - September 2003.

Robust and Optimal Control of Interconnected Systems
US National Science Foundation. July 2000 - June 2004.

Experimental Model-Based Control Design Using Multibody Codes
US National Science Foundation. June 1998 - May 2000.

Synthesis Methods for Distributed and Time Varying Controlled Systems
US Air Force Office of Scientific Research. April 1998 - November 2000.

Reduced Order Modeling and Control of Systems Subject to Fluid-Structure Interactions
US Air Force Office of Scientific Research. March 1998 - August 1999.

Mechatronics Systems Engineering Projects
Cornell College of Engineering laboratory and personnel funds. September 1998 - May 2005.

CO-PRINCIPAL INVESTIGATOR

EuRoC: European Robotics Challenges
European Research Council. January 2014 - December 2017.

NCCR Digital Fabrication
Swiss National Science Foundation. July 2014 - December 2015.

RoboEarth: Robots Sharing a Knowledge Base for World Modeling and Learning of Actions
European Research Council. January 2010 - December 2013.

Layered Fault Management Architectures
DARPA. September 2002 - August 2003.

Human Centered, Variable Initiative Control of Complex Automa-Teams
DARPA. September 2001 - September 2003.

Mixed Initiative Control of Automa-Teams
DARPA. September 2001 - December 2003.

Cooperative Control in Uncertain, Adversarial Environments
US Air Force Office of Scientific Research Multi-Disciplinary University Research Initiative. May 2001 - April 2006.

High Speed and High Precision Measurement and Simulation Design Laboratory
Cornell College of Engineering. January 2000.

A Practical Method to Predict and Control Non-linear Aeroelasticity
US Department of Defense. August 1999 - August 2000.

Three-Axis satellite Attitude Control Using Only Magnetic Torquers
US Air Force Office of Scientific Research. April 1999 - March 2000.

MENTORING

Ph.D.

Carmelo Sferrazza, Ph.D., ETH Zurich. Est. 2021.
Matthias Hofer, Ph.D., ETH Zurich. Est. 2021.
Rajan Gill, Ph.D., ETH Zurich. 2020.
Anton Ledergerber, Ph.D., ETH Zurich. 2020.
Mike Hamer, Ph.D., ETH Zurich, 2019.
Dario Brescianini, Ph.D., ETH Zurich, 2018.
Michael Muehlebach, Ph.D., ETH Zurich, 2017.
Robin Ritz, Ph.D., ETH Zurich, 2017.
Max Kriegleder, Ph.D., ETH Zurich, 2017.
Federico Augugliaro, Ph.D., ETH Zurich, 2015.
Mark Mueller, Ph.D., ETH Zurich, 2015.
Philipp Reist, Ph.D., ETH Zurich, 2015.
Gajamohan Mohanarajah, Ph.D., ETH Zurich, 2014.
Markus Hehn, Ph.D., ETH Zurich, 2014.

Sergei Lupashin, Ph.D., ETH Zurich, 2013.
Raymond Oung, Ph.D., ETH Zurich, 2013.
Sebastian Trimpe, Ph.D., ETH Zurich, 2013.
Angela Schoellig, Ph.D., ETH Zurich, 2012.
Michael Sherback, Ph.D., Cornell University, 2009.
Oliver Purwin, Ph.D., Cornell University, 2008.
Ramu Chandra, Ph.D., Cornell University, 2005.
Jeffrey Fowler, Ph.D., Cornell University, 2005.
Cedric Langbort, Ph.D, Cornell University, 2004.
Matthew Earl, Ph.D., Cornell University, 2004.

Post-Doctoral

Dr. Luca Gherardi. 2013 - 2014.
Dr. Markus Waibel. 2010 - 2014.
Dr. Michael Sherback. 2009 - 2010.
Dr. Frederic Bourgault. 2008 - 2010.
Dr. Guillaume Ducard. 2008 - 2009.
Dr. Keyong Li. 2005 - 2007.
Dr. Venkatesh Rao. 2004 - 2006.
Dr. JinWoo Lee. 1998 - 1999, 2001 - 2006.
Dr. Myungsoo Jun. 2001 - 2004.
Dr. Tama's Kalma'r Nagy. 2001 - 2002.

High-Profile Talks

Carlo Sferazza, TEDx 2021.
Carlo Sferazza, World.Minds 2019.
Léa Pereyre, World.Minds 2016.
Federico Augugliaro, TEDx 2016.
Angela Schoellig, TEDx 2016.
Max Kriegleder, TEDx 2015.
Gajan Mohanarajah, TEDx 2014.
Markus Hehn, TEDx 2014.
Sergei Lupashin, TED 2014.
Mark Mueller, TEDx 2014.
Federico Augugliaro, BUILDx 2014.
Raymond Oung and Max Kriegleder, World.Minds 2013.
Gajan Mohanarajah, World.Minds 2013.
Philipp Reist, World.Minds 2011.
Geo Robson, World.Minds 2009.
Sergei Lupashin, World.Minds 2008.

Major Ph.D. Awards

Michael Muehlebach, Branco Weiss Fellow 2018.
Michael Muehlebach, ETH Medal 2018.
Mark Mueller, ETH Medal 2016.
Mark Mueller, Georges Giralt Ph.D. Award 2016 .
Markus Hehn, Jakob Ackeret Award 2014.
Sebastian Trimpe, Klaus Tschira Award 2014.
Angela Schoellig, ETH Medal 2012.
Angela Schoellig, Dimitris N. Chorafas Foundation Award 2012.

APPENDIX B

Raffaello D'Andrea

ETH Zurich

Robotics & Machine Learning
Systems and Control

	All	Since 2016
Citations	16564	9641
h-index	67	53
i10-index	216	156

7 articles — not available

37 articles — available

Based on funding mandates

TITLE	CITED BY	YEAR
Distributed control design for spatially interconnected systems R D'Andrea, GE Dullerud IEEE Transactions on automatic control 48 (9), 1478-1495	904	2003
Coordinating hundreds of cooperative, autonomous vehicles in warehouses PR Wurman, R D'Andrea, M Mountz AI magazine 29 (1), 9	682	2008
Roboearth M Waibel, M Beetz, J Civera, R d'Andrea, J Elfring, D Galvez-Lopez, ... IEEE Robotics & Automation Magazine 18 (2), 69-82	527 *	2011
Distributed control design for systems interconnected over an arbitrary graph C Langbort, RS Chandra, R D'Andrea IEEE Transactions on Automatic Control 49 (9), 1502-1519	470	2004
A simple learning strategy for high-speed quadrocopter multi-flips S Lupashin, A Schöllig, M Sherback, R D'Andrea 2010 IEEE International Conference on Robotics and Automation, 1642-1648	397	2010
Method and system for transporting inventory items R D'andrea, PK Mansfield, MC Mountz, D Polic, PR Dingle US Patent 8,280,547	316	2012
Near-optimal dynamic trajectory generation and control of an omnidirectional vehicle T Kalmár-Nagy, R D’Andrea, P Ganguly Robotics and Autonomous Systems 46 (1), 47-64	284	2004
Stability and control of a quadrocopter despite the complete loss of one, two, or three propellers MW Mueller, R D'Andrea 2014 IEEE International Conference on Robotics and Automation (ICRA), 45-52	261	2014
The flight assembled architecture installation: Cooperative construction with flying machines F Augugliaro, S Lupashin, M Hamer, C Male, M Hehn, MW Mueller, ... IEEE Control Systems Magazine 34 (4), 46-64	254	2014
System and method for transporting inventory items PR Wurman, R D'andrea, MT Barbehenn, AE Hoffman, MC Mountz US Patent 7,912,574	236	2011

TITLE	CITED BY	YEAR
Rapyuta: A cloud robotics platform G Mohanarajah, D Hunziker, R D'Andrea, M Waibel IEEE Transactions on Automation Science and Engineering 12 (2), 481-493	232	2014
A platform for aerial robotics research and demonstration: The Flying Machine Arena S Lupashin, M Hehn, MW Mueller, AP Schoellig, M Sherback, R D'Andrea Mechatronics 24 (1), 41-54	232	2014
Generation of collision-free trajectories for a quadrocopter fleet: A sequential convex programming approach F Augugliaro, AP Schoellig, R D'Andrea 2012 IEEE/RSJ international conference on Intelligent Robots and Systems …	224	2012
Quadrocopter trajectory generation and control M Hehn, R D'Andrea IFAC Proceedings Volumes 44 (1), 1485-1491	216	2011
Guest editorial can drones deliver? R D'Andrea IEEE Transactions on Automation Science and Engineering 11 (3), 647-648	215	2014
A flying inverted pendulum M Hehn, R D'Andrea 2011 IEEE International Conference on Robotics and Automation, 763-770	212	2011
Distributed control of heterogeneous systems GE Dullerud, R D'Andrea IEEE Transactions on Automatic Control 49 (12), 2113-2128	207	2004
Event-based state estimation with variance-based triggering S Trimpe, R D'Andrea IEEE Transactions on Automatic Control 59 (12), 3266-3281	202	2014
Iterative MILP methods for vehicle-control problems MG Earl, R D'Andrea IEEE Transactions on Robotics 21 (6), 1158-1167	191	2005
Quadrocopter ball juggling M Müller, S Lupashin, R D'Andrea 2011 IEEE/RSJ international conference on Intelligent Robots and Systems …	187	2011
System and method for positioning a mobile drive unit AE Hoffman, MT Barbehenn, MC Mountz, PR Wurman, R D'andrea US Patent 9,087,314	185	2015
Rapyuta: The roboearth cloud engine D Hunziker, M Gajamohan, M Waibel, R D'Andrea Robotics and Automation (ICRA), 2013 IEEE International Conference on, 438-444	175	2013
Path planning for unmanned aerial vehicles in uncertain and adversarial environments M Jun, R D'Andrea Cooperative control: models, applications and algorithms, 95-110	174	2003

TITLE	CITED BY	YEAR
Inventory system with mobile drive unit and inventory holder MC Mountz, R D'andrea, JA LaPlante, PLII David, PK Mansfield, ... US Patent 7,402,018	171	2008
A computationally efficient motion primitive for quadrocopter trajectory generation MW Mueller, M Hehn, R D'Andrea IEEE Transactions on Robotics 31 (6), 1294-1310	165	2015
System and method for coordinating movement of mobile drive units R D'andrea, PR Wurman, MT Barbehenn, AE Hoffman, MC Mountz US Patent 7,920,962	165 *	2011
System and method for managing mobile drive units R D'andrea, PR Wurman, MT Barbehenn, AE Hoffman, MC Mountz US Patent 7,873,469	164	2011
Design, modeling and control of an omni-directional aerial vehicle D Brescianini, R D'Andrea 2016 IEEE international conference on robotics and automation (ICRA), 3261-3266	163	2016
Aerial robotic construction towards a new field of architectural research J Willmann, F Augugliaro, T Cadalbert, R D'Andrea, F Gramazio, M Kohler International journal of architectural computing 10 (3), 439-459	157	2012
Guest editorial: A revolution in the warehouse: A retrospective on kiva systems and the grand challenges ahead R D'Andrea IEEE Transactions on Automation Science and Engineering 4 (9), 638-639	157	2012
Trajectory generation and control for four wheeled omnidirectional vehicles O Purwin, R D'Andrea Robotics and Autonomous Systems 54 (1), 13-22	146	2006
Trajectory generation for four wheeled omnidirectional vehicles O Purwin, R D'Andrea Proceedings of the 2005, American Control Conference, 2005., 4979-4984	~~146~~ *	2005
Optimization-based iterative learning for precise quadrocopter trajectory tracking AP Schoellig, FL Mueller, R D'Andrea Autonomous Robots 33 (1-2), 103-127	145	2012
Cooperative quadrocopter ball throwing and catching R Ritz, MW Müller, M Hehn, R D'Andrea 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems …	143	2012
Fusing ultra-wideband range measurements with accelerometers and rate gyroscopes for quadrocopter state estimation MW Mueller, M Hamer, R D'Andrea 2015 IEEE International Conference on Robotics and Automation (ICRA), 1730-1736	141	2015

TITLE	CITED BY	YEAR
System and method for maneuvering a mobile drive unit PR Wurman, R D'andrea, MT Barbehenn, AE Hoffman, DC Koehler, ... US Patent 8,649,899	125	2014
The distributed flight array R Oung, R D'Andrea Mechatronics 21 (6), 908-917	124	2011
The distributed flight array R Oung, R D'Andrea Mechatronics 21 (6), 908-917	~~124~~	2011
The cubli: A cube that can jump up and balance M Gajamohan, M Merz, I Thommen, R D'Andrea 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems …	117	2012
System and method for generating a path for a mobile drive unit PR Wurman, R D'andrea, MT Barbehenn, AE Hoffman, MC Mountz US Patent 8,538,692	115	2013
Cloud-based collaborative 3D mapping in real-time with low-cost robots G Mohanarajah, V Usenko, M Singh, R D'Andrea, M Waibel IEEE Transactions on Automation Science and Engineering 12 (2), 423-431	114	2015
System and method for positioning a mobile drive unit AE Hoffman, MT Barbehenn, MC Mountz, PR Wurman, R D'andrea US Patent 8,220,710	113	2012
System and Method for Maneuvering a Mobile Drive Unit R D'andrea US Patent App. 13/470,591	108	2013
Modeling and control of a multi-agent system using mixed integer linear programming MG Earl, R D'Andrea Proceedings of the 41st IEEE Conference on Decision and Control, 2002. 1 …	101	2002
Real-time trajectory generation for quadrocopters M Hehn, R D'Andrea IEEE Transactions on Robotics 31 (4), 877-892	99	2015
A linear matrix inequality approach to decentralized control of distributed parameter systems R D'Andrea Proceedings of the 1998 American Control Conference. ACC (IEEE Cat. No …	99	1998
A model predictive controller for quadrocopter state interception MW Mueller, R D'Andrea 2013 European Control Conference (ECC), 1383-1389	97	2013
Real-time attitude estimation techniques applied to a four rotor helicopter MG Earl, R D'Andrea 2004 43rd IEEE Conference on Decision and Control (CDC)(IEEE Cat. No …	97	2004

TITLE	CITED BY	YEAR
System and method for coordinating movement of mobile drive units R D'andrea, PR Wurman, MT Barbehenn, AE Hoffman, MC Mountz US Patent 8,412,400	~~96~~	2013
System and method for coordinating movement of mobile drive units R D'andrea, PR Wurman, MT Barbehenn, AE Hoffman, MC Mountz US Patent 8,412,400	96	2013
A robot self-localization system using one-way ultra-wideband communication A Ledergerber, M Hamer, R D'Andrea 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems …	90	2015
Rotating stall control of an axial flow compressor using pulsed air injection R D’andrea, RL Behnken, RM Murray Journal of turbomachinery 119 (4), 742-752	90	1997
Distributed control of systems over discrete groups B Recht, R D'Andrea IEEE Transactions on Automatic Control 49 (9), 1446-1452	88	2004
System and method for inventory management using mobile drive units AE Hoffman, MC Mountz, MT Barbehenn, JR Allard, ME Kimmel, F Santini, ... US Patent 8,831,984	87	2014
Future challenges of coordinating hundreds of autonomous vehicles in distribution facilities R D'Andrea, P Wurman 2008 IEEE International Conference on Technologies for Practical Robot …	86	2008
Kalman decomposition of linear fractional transformation representations and minimality R D'Andrea, S Khatri Proceedings of the 1997 American Control Conference (Cat. No. 97CH36041) 6 …	86	1997
Building tensile structures with flying machines F Augugliaro, A Mirjan, F Gramazio, M Kohler, R D'Andrea 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems …	85	2013
A decomposition approach to multi-vehicle cooperative control MG Earl, R D’Andrea Robotics and Autonomous Systems 55 (4), 276-291	84	2007
A computationally efficient algorithm for state-to-state quadrocopter trajectory generation and feasibility verification MW Mueller, M Hehn, R D'Andrea 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems …	82	2013
Nonlinear analysis and control of a reaction-wheel-based 3-D inverted pendulum M Muehlebach, R D’Andrea IEEE Transactions on Control Systems Technology 25 (1), 235-246	~~79~~	2016

TITLE	CITED BY	YEAR
Nonlinear analysis and control of a reaction-wheel-based 3-D inverted pendulum M Muehlebach, R D'Andrea IEEE Transactions on Control Systems Technology 25 (1), 235-246	79	2016
Relaxed hover solutions for multicopters: Application to algorithmic redundancy and novel vehicles MW Mueller, R D'Andrea The International Journal of Robotics Research 35 (8), 873-889	78	2016
Constructing a testbed for research in control of interconnected systems. JM Fowler, R D'Andrea IEEE Control Systems Magazine 272, 03	78 *	1708
The flying machine arena as of 2010 S Lupashin, A Schöllig, M Hehn, R D'Andrea 2011 IEEE International Conference on Robotics and Automation, 2970-2971	75	2011
An experimental demonstration of a distributed and event-based state estimation algorithm S Trimpe, R D'Andrea IFAC Proceedings Volumes 44 (1), 8811-8818	75	2011
Stabilization of a flying vehicle on a taut tether using inertial sensing S Lupashin, R D'Andrea 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems …	70	2013
Distributed control of close formation flight JM Fowler, R D'Andrea Proceedings of the 41st IEEE Conference on Decision and Control, 2002. 3 …	70	2002
Admittance control for physical human-quadrocopter interaction F Augugliaro, R D'Andrea 2013 European Control Conference (ECC), 1805-1810	69	2013
Performance benchmarking of quadrotor systems using time-optimal control M Hehn, R Ritz, R D'Andrea Autonomous Robots 33 (1-2), 69-88	69	2012
Quadrocopter pole acrobatics D Brescianini, M Hehn, R D'Andrea 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems …	68	2013
The roboflag testbed R D'Andrea, M Babish Proceedings of the 2003 American Control Conference, 2003. 1, 656-660	68	2003
The Cubli: A reaction wheel based 3D inverted pendulum M Gajamohan, M Muehlebach, T Widmer, R D'Andrea IMU 2 (2)	67	2013
Method and system for transporting inventory items R D'andrea, PK Mansfield, MC Mountz, D Polic, PR Dingle US Patent 9,436,184	65	2016

TITLE	CITED BY	YEAR
Method and system for transporting inventory items R D'andrea, PK Mansfield, MC Mountz, D Polic, PR Dingle US Patent 9,436,184	65	2016
Nonlinear system identification of multi-degree-of-freedom systems M Thothadri, RA Casas, FC Moon, R D'andrea, CR Johnson Nonlinear Dynamics 32 (3), 307-322	65	2003
Control of rotating stall in a low-speed axial flow compressor using pulsed air injection: Modeling, simulations, and experimental validation RL Behnken, R D'Andrea, RM Murray Proceedings of 1995 34th IEEE Conference on Decision and Control 3, 3056-3061	65	1995
The roboflag competition R D'Andrea, RM Murray Proceedings of the 2003 American Control Conference, 2003. 1, 650-655	63	2003
System and method for maneuvering a mobile drive unit R D'Andrea US Patent 10,093,526	62 *	2018
Nonlinear Quadrocopter Attitude Control: Technical Report D Brescianini, M Hehn, R D'Andrea ETH Zurich	~~62~~	2013
Nonlinear quadrocopter attitude control: Technical report D Brescianini, M Hehn, R D'Andrea ETH Zurich	62	2013
Autonomous quadrotor flight using a vision system and accommodating frames misalignment G Ducard, R D'Andrea 2009 IEEE International Symposium on Industrial Embedded Systems, 261-264	61	2009
Performing aggressive maneuvers using iterative learning control O Purwin, R D'Andrea 2009 IEEE International Conference on Robotics and Automation, 1731-1736	61	2009
Carrying a flexible payload with multiple flying vehicles R Ritz, R D'Andrea 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems …	60	2013
Theory and implementation of path planning by negotiation for decentralized agents O Purwin, R D’Andrea, JW Lee Robotics and Autonomous Systems 56 (5), 422-436	60	2008
Computational study and comparisons of LFT reducibility methods C Beck, R D'Andrea Proceedings of the 1998 American Control Conference. ACC (IEEE Cat. No …	58	1998
Synchronizing the motion of a quadrocopter to music A Schöllig, F Augugliaro, S Lupashin, R D'Andrea 2010 IEEE International Conference on Robotics and Automation, 3355-3360	56	2010

TITLE	CITED BY	YEAR
Distributed control of spatially reversible interconnected systems with boundary conditions C Langbort, R D'Andrea SIAM journal on control and optimization 44 (1), 1-28	55	2005
Using airborne vehicle-based antenna arrays to improve communications with UAV clusters SH Breheny, R D'Andrea, JC Miller 42nd IEEE International Conference on Decision and Control (IEEE Cat. No …	55	2003
A world wide web for robots M Waibel, M Beetz, J Civera, R d'Andrea, J Elfring, D Galvez-Lopez, ... IEEE Robotics & Automation Magazine 18 (2), 69-82	~~54~~	2011
RoboEarth: connecting robots worldwide O Zweigle, R van de Molengraft, R d'Andrea, K Häussermann Proceedings of the 2nd International Conference on Interaction Sciences …	54	2009
Low observability path planning for an unmanned air vehicle using mixed integer linear programming A Chaudhry, K Misovec, R D'Andrea 2004 43rd IEEE Conference on Decision and Control (CDC)(IEEE Cat. No …	54	2004
Real-time trajectory generation for omnidirectional vehicles T Kalmár-Nagy, P Ganguly, R D'Andrea Proceedings of the 2002 American Control Conference (IEEE Cat. No. CH37301 …	53	2002
Controlled flight of a multicopter experiencing a failure affecting an effector MW Mueller, S Lupashin, R D'andrea, M Waibel US Patent 9,856,016	~~51~~	2018
Controlled flight of a multicopter experiencing a failure affecting an effector MW Mueller, S Lupashin, R D'andrea, M Waibel US Patent 9,856,016	51	2018
Method and system for transporting inventory items R D'Andrea, PK Mansfield, MC Mountz, D Polic, PR Dingle US Patent 10,112,771	50 *	2018
Distributed control design with robustness to small time delays RS Chandra, C Langbort, R D'Andrea Systems & Control Letters 58 (4), 296-303	50	2009
System and method for managing mobile drive units R D'andrea, PR Wurman, MT Barbehenn, AE Hoffman, MC Mountz US Patent 8,068,978	~~49~~	2011
System and method for managing mobile drive units R D'andrea, PR Wurman, MT Barbehenn, AE Hoffman, MC Mountz US Patent 8,068,978	~~49~~	2011
Optimization-based iterative learning control for trajectory tracking A Schöllig, R D'Andrea 2009 European Control Conference (ECC), 1505-1510	49	2009

TITLE	CITED BY	YEAR
Alphabet soup: A testbed for studying resource allocation in multi-vehicle systems CJ Hazard, PR Wurman, R D’Andrea Proceedings of AAAI Workshop on Auction Mechanisms for Robot Coordination, 23-30	49	2006
Adaptive fast open-loop maneuvers for quadrocopters S Lupashin, R D’Andrea Autonomous Robots 33 (1-2), 89-102	48	2012
Method and system for transporting inventory items R D'andrea, PK Mansfield, MC Mountz, D Polic, PR Dingle US Patent 8,170,711	~~48~~	2012
Quadrocopter performance benchmarking using optimal control R Ritz, M Hehn, S Lupashin, R D'Andrea 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems …	48	2011
Accelerometer-based tilt estimation of a rigid body with only rotational degrees of freedom S Trimpe, R D'Andrea 2010 IEEE International Conference on Robotics and Automation, 2630-2636	48	2010
A frequency domain iterative learning algorithm for high-performance, periodic quadrocopter maneuvers M Hehn, R D’Andrea Mechatronics 24 (8), 954-965	47	2014
Robotics in edutainment M Asada, R D'Andrea, A Birk, H Kitano, M Veloso Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference …	47	2000
Generalized l 2 synthesis R D'Andrea IEEE transactions on Automatic Control 44 (6), 1145-1156	47	1999
Iterative learning of feed-forward corrections for high-performance tracking FL Mueller, AP Schoellig, R D'Andrea 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems …	46	2012
Dance of the flying machines: Methods for designing and executing an aerial dance choreography F Augugliaro, AP Schoellig, R D'Andrea IEEE Robotics & Automation Magazine 20 (4), 96-104	44	2013
The cornell robocup team R D’Andrea, T Kalmar-Nagy, P Ganguly, M Babish Robot Soccer World Cup, 41-51	44	2000
Roboflag games using systems based, hierarchical control M Campbell, R D'Andrea, D Schneider, A Chaudhry, S Waydo, J Sullivan, ... Proceedings of the 2003 American Control Conference, 2003. 1, 661-666	42	2003
System identification of the crazyflie 2.0 nano quadrocopter J Förster, M Hamer, R D'Andrea	41	2015

TITLE	CITED BY	YEAR
A self-tuning LQR approach demonstrated on an inverted pendulum S Trimpe, A Millane, S Doessegger, R D'Andrea IFAC Proceedings Volumes 47 (3), 11281-11287	41	2014
The distributed flight array: Design, implementation, and analysis of a modular vertical take-off and landing vehicle R Oung, R D’Andrea The International Journal of Robotics Research 33 (3), 375-400	41	2014
Multi-vehicle cooperative control using mixed integer linear programming MG Earl, R D’Andrea Cooperative Control of Distributed Multi-Agent Systems, 231-259	41	2007
A global controller for flying wing tailsitter vehicles R Ritz, R D'Andrea 2017 IEEE international conference on robotics and automation (ICRA), 2731-2738	39	2017
A platform for dance performances with multiple quadrocopters A Schöllig, F Augugliaro, R D’Andrea Improving Tracking Performance by Learning from Past Data, 147	39	2012
Feasiblity of motion primitives for choreographed quadrocopter flight A Schöllig, M Hehn, S Lupashin, R D'Andrea Proceedings of the 2011 American Control Conference, 3843-3849	39	2011
Propeller thrust and drag in forward flight R Gill, R D'Andrea 2017 IEEE Conference on Control Technology and Applications (CCTA), 73-79	38	2017
Control of spatially varying distributed systems GE Dullerud, R D'Andrea, SG Lall Proceedings of the 37th IEEE Conference on Decision and Control (Cat. No …	38	1998
Building a Bridge with Flying Robots A Mirjan, F Augugliaro, R D’Andrea, F Gramazio, M Kohler Robotic Fabrication in Architecture, Art and Design 2016, 34-47	37	2016
The Balancing Cube: A dynamic sculpture as test bed for distributed estimation and control S Trimpe, R D’Andrea IEEE Control Systems Magazine 32 (6), 48-75	37	2012
Linear matrix inequalities, multidimensional system optimization, and control of spatially distributed systems: An example R D'Andrea Proceedings of the 1999 American Control Conference (Cat. No. 99CH36251) 4 …	37	1999
Minimality, controllability and observability for uncertain systems C Beck, R D'Andrea Proceedings of the 1997 American Control Conference (Cat. No. 97CH36041) 5 …	37	1997
Adaptive open-loop aerobatic maneuvers for quadrocopters S Lupashin, R D'Andrea IFAC Proceedings Volumes 44 (1), 2600-2606	36	2011

TITLE	CITED BY	YEAR
Design and analysis of a blind juggling robot P Reist, R D'Andrea IEEE Transactions on Robotics 28 (6), 1228-1243	35	2012
Feed-forward parameter identification for precise periodic quadrocopter motions AP Schoellig, C Wiltsche, R D'Andrea 2012 American Control Conference (ACC), 4313-4318	35	2012
Robot soccer: A platform for systems engineering R D’Andrea age 4, 1	35	2000
Behavioral approach to robustness analysis F Paganini, R D'Andrea, J Doyle Proceedings of 1994 American Control Conference-ACC'94 3, 2782-2786	35	1994
Interconnection of uncertain behavioral systems for robust control R D'Andrea, F Paganini Proceedings of 32nd IEEE Conference on Decision and Control, 3642-3647	35	1993
Method and system for transporting inventory items R D'andrea, PK Mansfield, MC Mountz, D Polic, PR Dingle US Patent 8,725,286	34	2014
Distributed control of antenna array with formation of uavs S Tonetti, M Hehn, S Lupashin, R D'Andrea IFAC Proceedings Volumes 44 (1), 7848-7853	33	2011
Design, Motivation and Evaluation of a Full-Resolution Optical Tactile Sensor C Sferrazza, R D’Andrea Sensors 19 (4), 928	32	2019
Robotic calligraphy—learning how to write single strokes of Chinese and Japanese characters S Mueller, N Huebel, M Waibel, R D'Andrea 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems …	32	2013
Method and system for transporting inventory items R D'andrea, PK Mansfield, MC Mountz, D Polle, PR Dingle US Patent 8,280,546	32	2012
Method and system for transporting inventory items R D'andrea, PK Mansfield, MC Mountz, D Polle, PR Dingle US Patent 8,280,546	32	2012
Performing and extending aggressive maneuvers using iterative learning control O Purwin, R D’Andrea Robotics and Autonomous Systems 59 (1), 1-11	32	2011
Covariance Correction Step for Kalman Filtering with an Attitude MW Mueller, M Hehn, R D’Andrea Journal of Guidance, Control, and Dynamics, 1-7	31	2016

TITLE	CITED BY	YEAR
Real-time trajectory generation for interception maneuvers with quadrocopters M Hehn, R D'Andrea 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems …	31	2012
Bouncing an unconstrained ball in three dimensions with a blind juggling robot P Reist, R D'Andrea 2009 IEEE International Conference on Robotics and Automation, 1774-1781	31	2009
Convex/spl Lscr//sub 2/synthesis for multidimensional systems RA D'Andrea, GE Dullerund, S Lall Proceedings of the 37th IEEE Conference on Decision and Control (Cat. No …	31	1998
Self-calibrating ultra-wideband network supporting multi-robot localization M Hamer, R D'Andrea IEEE Access 6, 22292-22304	30	2018
System and method for inventory management using mobile drive units AE Hoffman, MC Mountz, MT Barbehenn, JR Allard, ME Kimmel, F Santini, ... US Patent 9,317,034	30	2016
So you think you can dance? rhythmic flight performances with quadrocopters AP Schoellig, H Siegel, F Augugliaro, R D'Andrea Controls and Art, 73-105	30	2014
System and method for managing mobile drive units R D'andrea, PR Wurman, MT Barbehenn, AE Hoffman, MC Mountz US Patent 8,265,873	29	2012
Real-time motion planning and control in the 2005 cornell robocup system M Sherback, O Purwin, R D'Andrea Robot Motion and Control, 245-263	29	2006
Distributed control of heterogeneous systems interconnected over an arbitrary graph C Langbort, R D'Andrea 42nd IEEE International Conference on Decision and Control (IEEE Cat. No …	29	2003
MATHEMATICAL SYSTEMS THEORY IN BIOLOGY, COMMUNICATION, COMPUTATION, AND FINANCE MS Alber, MA Kiskowski, JA Glazier, Y Jiang, GB Arous, A Tannenbaum, ... On cellular automaton approaches to modeling biological cells	29 *	2003
A controllable flying vehicle with a single moving part W Zhang, MW Mueller, R D'Andrea 2016 IEEE International Conference on Robotics and Automation (ICRA), 3275-3281	28	2016
Generating a path for a mobile drive unit PR Wurman, R D'andrea, MT Barbehenn, AE Hoffman, MC Mountz US Patent 8,930,133	28	2015
A decomposition approach to distributed analysis of networked systems C Langbort, L Xiao, R D'Andrea, S Boyd 2004 43rd IEEE Conference on Decision and Control (CDC)(IEEE Cat. No …	28	2004

TITLE	CITED BY	YEAR
Probability map building of uncertain dynamic environments with indistinguishable obstacles M Jun, R D'Andrea Proceedings of the 2003 American Control Conference, 2003. 4, 3417-3422	28	2003
Uncertain behavior R D'Andrea, F Paganini, JC Doyle California Institute of Technology	28	1993
Transporting inventory items using mobile drive units and conveyance equipment PR Wurman, R D'andrea, MT Barbehenn, AE Hoffman, MC Mountz US Patent 9,519,284	27	2016
Application of distributed control techniques to the adaptive secondary mirror of Cornell's Large Atacama Telescope J Kulkarni, R D'Andrea, B Brandl Adaptive Optical System Technologies II 4839, 750-757	27	2003
Software for modeling, analysis, and control design for multidimensional systems R D'Andrea Proceedings of the 1999 IEEE International Symposium on Computer Aided …	27	1999
A state-space theory of uncertain systems C Beck, R D'Andrea, F Paganini, WM Lu, J Doyle IFAC Proceedings Volumes 29 (1), 3162-3167	27	1996
$H\infty$ optimization with spatial constraints R D'Andrea Decision and Control, 1995., Proceedings of the 34th IEEE Conference on 4 …	27	1995
Application of an approximate model predictive control scheme on an unmanned aerial vehicle M Hofer, M Muehlebach, R D'Andrea 2016 IEEE International Conference on Robotics and Automation (ICRA), 2952-2957	26	2016
Imposing boundary conditions for a class of spatially-interconnected systems C Langbort, R D'Andrea Proceedings of the 2003 American Control Conference, 2003. 1, 107-112	26	2003
Flying camera with string assembly for localization and interaction M Waibel, S Lupashin, M Hehn, R D'andrea US Patent 9,753,355	~~25~~	2017
Flying camera with string assembly for localization and interaction M Waibel, S Lupashin, M Hehn, R D'andrea US Patent 9,753,355	25	2017
Flight Assembled Architecture F Gramazio, M Kohler, R D'Andrea Editions HYX	25	2012

TITLE	CITED BY	YEAR
On the peaking phenomenon in the control of vehicular platoons MR Jovanović, JM Fowler, B Bamieh, R D'Andrea Systems & Control Letters 57 (7), 528-537	25	2008
Noncommuting multidimensional realization theory: Minimality, reachability, and observability C Beck, R D'Andrea IEEE Transactions on Automatic Control 49 (10), 1815-1822	25	2004
A state space approach to control of interconnected systems R D'Andrea, C Langbort, R Chandra Mathematical Systems Theory in Biology, Communications, Computation, and …	25	2003
The Navigation of Autonomous Vehicles in Uncertain Dynamic Environments: A Case Study (I) M Jun, AI Chaudhry, R D Andrea IEEE Conference on Decision and Control 4, 3770-3775	25	2002
H∞ optimal interconnections R D'Andrea Systems & control letters 32 (5), 313-322	25 *	1997
Ultra-wideband range measurement model with Gaussian processes A Ledergerber, R D'Andrea 2017 IEEE Conference on Control Technology and Applications (CCTA), 1929-1934	24	2017
Feasibility of a distributed flight array R Oung, A Ramezani, R D'Andrea Proceedings of the 48h IEEE Conference on Decision and Control (CDC) held …	24	2009
Critical subsystem failure mitigation in an indoor UAV testbed. MW Mueller, R D'Andrea IROS, 780-785	23	2012
Independent vs. joint estimation in multi-agent iterative learning control A Schöllig, J Alonso-Mora, R D'Andrea 49th IEEE Conference on Decision and Control (CDC), 6949-6954	23	2010
The Cornell RoboCup Robot Soccer Team: 1999–2003 R D'Andrea Handbook of Networked and Embedded Control Systems, 793-804	23	2005
Control of spatially interconnected discrete-time systems R D'Andrea, RS Chandra Proceedings of the 41st IEEE Conference on Decision and Control, 2002. 1 …	23	2002
A study in cooperative control: The Roboflag drill MG Earl, R D'Andrea Proceedings of the 2002 American Control Conference (IEEE Cat. No. CH37301 …	23	2002
System and method for coordinating movement of mobile drive units R D'andrea, PR Wurman, MT Barbehenn, AE Hoffman, MC Mountz US Patent 9,740,212	~~22~~	2017

TITLE	CITED BY	YEAR
Asynchronous implementation of a distributed average consensus algorithm M Kriegleder, R Oung, R D'Andrea 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems …	22	2013
Knowledge transfer for high-performance quadrocopter maneuvers M Hamer, M Waibel, R D'Andrea 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems …	22	2013
A scaled small gain theorem with applications to spatially interconnected systems RS Chandra, R D'Andrea IEEE Transactions on Automatic Control 51 (3), 465-469	22	2006
Convex and finite-dimensional conditions for controller synthesis with dynamic integral constraints R D'Andrea IEEE Transactions on Automatic Control 46 (2), 222-234	22	2001
Active control of rotating stall using pulsed-air injection: a parametric study on a low-speed axial flow compressor R D'Andrea, RL Behnken, RM Murray SPIE's 1995 Symposium on OE/Aerospace Sensing and Dual Use Photonics, 152-165	22	1995
Computationally Efficient Trajectory Generation for Fully Actuated Multirotor Vehicles D Brescianini, R D'Andrea IEEE Transactions on Robotics 34 (3), 555-571	21	2018
High-speed, steady flight with a quadrocopter in a confined environment using a tether M Schulz, F Augugliaro, R Ritz, R D'Andrea 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems …	21	2015
Architectural fabrication of tensile structures with flying machines A Mirjan, F Gramazio, M Kohler, F Augugliaro, R D'Andrea Green Design, Materials and Manufacturing Processes, 513-518	20	2013
Antenna array synthesis with clusters of unmanned aerial vehicles RS Chandra, SH Breheny, R D'Andrea Automatica 44 (8), 1976-1984	20	2008
System and method for maneuvering a mobile drive unit R D'andrea US Patent App. 14/586,596	~~19~~	2018
Knot-tying with flying machines for aerial construction F Augugliaro, E Zarfati, A Mirjan, R D'Andrea 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems …	19	2015
Towards robotic calligraphy N Huebel, E Mueggler, M Waibel, R D'Andrea 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems …	19	2012

TITLE	CITED BY	YEAR
Aerial vehicle M Hehn, M Waibel, L Gherardi, R D'andrea US Patent 10,766,627	18	2020
An omni-directional multirotor vehicle D Brescianini, R D'Andrea Mechatronics 55, 76-93	18	2018
An iterative learning scheme for high performance, periodic quadrocopter trajectories M Hehn, R D'Andrea 2013 European Control Conference (ECC), 1799-1804	18	2013
Active vibro-acoustic control of a flexible beam using distributed control E Scholte, R D'Andrea Proceedings of the 2003 American Control Conference, 2003. 3, 2640-2645	18	2003
LMI approach to mixed H-2 and H-infinity performance objective controller design R D'Andrea IFAC Proceedings Volumes 29 (1), 3198-3203	18	1996
Ground truth force distribution for learning-based tactile sensing: a finite element approach C Sferrazza, A Wahlsten, C Trueeb, R D'Andrea IEEE Access 7, 173438-173449	17	2019
A global strategy for tailsitter hover control R Ritz, R D'Andrea Robotics Research, 21-37	17	2018
Time-optimal online trajectory generator for robotic manipulators F Ramos, M Gajamohan, N Huebel, R D'Andrea Eidgenössische Technische Hochschule Zürich, Institute for Dynamic Systems …	17	2013
Reduced communication state estimation for control of an unstable networked control system S Trimpe, R D'Andrea 2011 50th IEEE Conference on Decision and Control and European Control …	17	2011
Distributed control of inhomogeneous systems, with boundary conditions GE Dullerud, D D'Andrea Proceedings of the 38th IEEE Conference on Decision and Control (Cat. No …	17	1999
Transfer learning for vision-based tactile sensing C Sferrazza, R D'Andrea 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems …	16	2019
Method and system for transporting inventory items R D'andrea, PK Mansfield, MC Mountz, D Polic, PR Dingle US Patent 8,909,368	16	2014

TITLE	CITED BY	YEAR
Fast Generation of Collision-Free Trajectories for Robot Swarms Using GPU Acceleration M Hamer, L Widmer, R D’andrea IEEE Access 7, 6679-6690	15	2019
Methods and systems for scheduling the transmission of localization signals and operating self-localizing apparatus L Gherardi, R D'andrea, M Hehn, M Waibel US Patent 10,111,044	15	2018
Augmenting ultra-wideband localization with computer vision for accurate flight D Hoeller, A Ledergerber, M Hamer, R D’Andrea IFAC-PapersOnLine 50 (1), 12734-12740	15	2017
Adaptive highways on a grid H Roozbehani, R D’Andrea Robotics Research, 661-680	15	2011
Distributed adaptive output feedback control design and application to a formation flight experiment AT Kutay, JM Fowler, AJ Calise, R D’Andrea AIAA Guidance, Navigation and Control Conference	15	2005
Parametrized infinite-horizon model predictive control for linear time-invariant systems with input and state constraints M Muehlebach, R D'Andrea 2016 American Control Conference (ACC), 2669-2674	14	2016
The RoboFlag Game R D’Andrea, RM Murray, JA Adams, AT Hayes, M Campbell, A Chaudry American control conference, 661-666	14	2003
Control of interconnected systems of finite spatial extent RS Chandra, JM Fowler, R D'Andrea Proceedings of the 41st IEEE Conference on Decision and Control, 2002. 1 …	14	2002
Design, Modeling and Control of a Soft Robotic Arm M Hofer, R D'Andrea 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems …	13	2018
A frequency domain iterative feed-forward learning scheme for high performance periodic quadrocopter maneuvers M Hehn, R D'Andrea 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems …	13	2013
Iterative Learning Control for Fast and Accurate Position Tracking with an Articulated Soft Robotic Arm M Hofer, L Spannagl, R D'Andrea arXiv preprint arXiv:1901.10187	~~12~~	2019
Flying camera with string assembly for localization and interaction M Waibel, S Lupashin, M Hehn, R D'Andrea US Patent App. 10/168,601	12 *	2019

TITLE	CITED BY	YEAR
Iterative learning control for fast and accurate position tracking with a soft robotic arm M Hofer, L Spannagl, R D'Andrea Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.	12 *	2019
Method and system for transporting inventory items R D'andrea, PK Mansfield, MC Mountz, D Polic, PR Dingle US Patent 10,112,771	~~12~~	2018
Method and system for transporting inventory items R D'andrea, PK Mansfield, MC Mountz, D Polic, PR Dingle US Patent 10,112,771	~~12~~	2018
Method and system for transporting inventory items PR Wurman, R D'Andrea, MT Barbehenn, AE Hoffman, MC Mountz US Patent App. 10/067,501	12 *	2018
Calibrating Away Inaccuracies in Ultra Wideband Range Measurements: A Maximum Likelihood Approach A Ledergerber, R D'andrea IEEE Access 6, 78719-78730	12	2018
The Flying Platform–A testbed for ducted fan actuation and control design M Muehlebach, R D'Andrea Mechatronics 42, 52-68	12	2017
Limited benefit of joint estimation in multi-agent iterative learning AP Schoellig, J Alonso-Mora, R D'Andrea Asian Journal of Control 14 (3), 613-623	12	2012
Slower visuomotor corrections with unchanged latency are consistent with optimal adaptation to increased endogenous noise in the elderly M Sherback, FJ Valero-Cuevas, R D'Andrea PLoS computational biology 6 (3)	12	2010
Learning the sense of touch in simulation: a sim-to-real strategy for vision-based tactile sensing C Sferrazza, T Bi, R D'Andrea arXiv preprint arXiv:2003.02640	11	2020
Trajectory tracking and iterative learning on an unmanned aerial vehicle using parametrized model predictive control C Sferrazza, M Muehlebach, R D'Andrea 2017 IEEE 56th Annual Conference on Decision and Control (CDC), 5186-5192	11	2017
Longitudinal Stability Analysis of a Jet-Powered Wingsuit G Robson, R D'Andrea AIAA Atmospheric Flight Mechanics Conference, 7512	11	2010
On avoiding saturation in the control of vehicular platoons MR Jovanovic, JM Fowler, B Bamieh, R D'Andrea Proceedings of the 2004 American Control Conference 3, 2257-2262	11	2004

TITLE	CITED BY	YEAR
Simplification of spatially distributed systems C Beck, R D'Andrea Proceedings of the 38th IEEE Conference on Decision and Control (Cat. No …	11	1999
Controller synthesis for implicitly defined uncertain systems R D'Andrea, F Paganini Proceedings of 1994 33rd IEEE Conference on Decision and Control 4, 3679-3684	11	1994
Tilt-prioritized quadrocopter attitude control D Brescianini, R D'Andrea IEEE Transactions on Control Systems Technology 28 (2), 376-387	10	2018
Maneuvering a mobile drive unit PR Wurman, R D'andrea, MT Barbehenn, AE Hoffman, DC Koehler, ... US Patent 9,511,934	~~10~~	2016
Maneuvering a mobile drive unit PR Wurman, R D'andrea, MT Barbehenn, AE Hoffman, DC Koehler, ... US Patent 9,511,934	10	2016
Rendezvous with bearing-only information and limited sensing range M Kriegleder, ST Digumarti, R Oung, R D'Andrea 2015 IEEE International Conference on Robotics and Automation (ICRA), 5941-5947	10	2015
Design and implementation of a minimum time transition for an inverted pendulum M Earl, R D'Andrea Asian Conference on Industrial Automation and Robotics	10	2005
Experimental demonstrations of semi-autonomous control M Campbell, R D'Andrea, JW Lee, E Scholte Proceedings of the 2004 American Control Conference 6, 5338-5343	10	2004
Cornell Big Red 2003 O Purwin, R D'Andrea Robocup	10	2003
Big red: The cornell small league robot soccer team R D'Andrea, JW Lee, A Hoffman, A Samad-Yahaya, LB Cremean, ... Robot Soccer World Cup, 49-60	10	1999
Approximate behaviors JC Doyle, F Paganini, R D'Andrea, S Khatri Proceedings of 35th IEEE Conference on Decision and Control 1, 688-693	10	1996
Methods and systems for scheduling the transmission of localization signals and operating self-localizing apparatus L Gherardi, R D'Andrea, M Hehn, M Waibel US Patent 10,321,286	9 *	2019
A limiting property of the matrix exponential with application to multi-loop control S Trimpe, R D'Andrea Proceedings of the 48h IEEE Conference on Decision and Control (CDC) held …	9	2009

TITLE	CITED BY	YEAR
Active control of an axial flow compressor via pulsed air injection R D'Andrea, RL Behnken, RM Murray California Institute of Technology	9	1996
Synchronous reluctance motors for low-cost, medium performance drives N Balbo, R D'Andrea, L Malesani, P Tomasin 1993 Fifth European Conference on Power Electronics and Applications, 77-81	9	1993
System and method for coordinating movement of mobile drive units R D'andrea, PR Wurman, MT Barbehenn, AE Hoffman, MC Mountz US Patent 9,448,560	8	2016
System and method for coordinating movement of mobile drive units R D'andrea, PR Wurman, MT Barbehenn, AE Hoffman, MC Mountz US Patent 9,448,560	8	2016
Distributed altitude and attitude estimation from multiple distance measurements M Kriegleder, R Oung, R D'Andrea 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems …	8	2012
Design of the pendulum juggler P Reist, R D'Andrea 2011 IEEE International Conference on Robotics and Automation, 5154-5159	8	2011
Encapsulated path planning for abstraction-based control of multi-vehicle systems VG Rao, T Wongpiromsarn, T Ho, K Chung, R D'Andrea 2006 American Control Conference, 6 pp.	8	2006
Control of autonomous and semi-autonomous systems R D'Andrea Proceedings of the Fourth International Workshop on Robot Motion and Control …	8	2004
Design of full state feedback finite-precision controllers R D'Andrea, RSH Istepanian International Journal of Robust and Nonlinear Control 12 (6), 537-553	8	2002
Linear matrix inequality conditions for robustness and control design R D'Andrea International Journal of Robust and Nonlinear Control 11 (6), 541-554	8	2001
Generalized L 2 synthesis: a new framework for control design R D'Andrea Decision and Control, 1996., Proceedings of the 35th IEEE Conference on 4 …	8	1996
Method and system for transporting inventory items PR Wurman, R D'andrea, MT Barbehenn, AE Hoffman, MC Mountz US Patent 10,809,706	7	2020
Flexibly supported movable platform having an actuator to move a display R D'Andrea, L Gherardi, M Hehn, M Waibel US Patent App. 10/143,930	7 *	2018

TITLE	CITED BY	YEAR
Flexibly supported movable platform having an actuator to move a display R D'andrea, L Gherardi, M Hehn, M Waibel US Patent App. 14/757,950	~~7~~	2018
Flexibly supported movable platform having an actuator to move a display R D'andrea, L Gherardi, M Hehn, M Waibel US Patent 10,143,930	7	2018
Methods and systems for scheduling the transmission of localization signals and operating self-localizing apparatus L Gherardi, R D'andrea, M Hehn, M Waibel US Patent 9,661,472	7	2017
An on-board learning scheme for open-loop quadrocopter maneuvers using inertial sensors and control inputs from an external pilot R Ritz, R D'Andrea 2014 IEEE International Conference on Robotics and Automation (ICRA), 5245-5251	7	2014
Visuomotor optimality and its utility in parametrization of response M Sherback, R D'Andrea IEEE Transactions on Biomedical Engineering 55 (7), 1783-1791	7	2008
Path planning by negotiation for decentralized agents O Purwin, R D'Andrea 2007 American Control Conference, 5296-5301	7	2007
Extension of Parrott's theorem to nondefinite scalings R D'Andrea IEEE Transactions on Automatic Control 45 (5), 937-940	7	2000
Necessary and sufficient conditions for gain scheduling subject to full-structured uncertainty R D'Andrea Proceedings of 35th IEEE Conference on Decision and Control 4, 3760-3765	7	1996
A Multi-Static Radar Network with Ultra-Wideband Radio-Equipped Devices A Ledergerber, R D’Andrea Sensors 20 (6), 1599	6	2020
Method and system for transporting inventory items PR Wurman, R D'andrea, MT Barbehenn, AE Hoffman, MC Mountz US Patent 10,133,267	6	2018
Cooperative Control M Hehn, M Hamer, J Willmann, M Kohler, P Heckeroth, R D’Andrea, ... IEEE CONTROL SYSTEMS MAGAZINE	6	2014
Two Approaches to Dynamic Refinement in Hierarchical Motion Planning T Wongpiromsarn, VG Rao, R D’Andrea AIAA Guidance, Navigation and Control Conference	6	2005
Necessity of the small gain theorem for multidimensional systems RS Chandra, R D'Andrea 42nd IEEE International Conference on Decision and Control (IEEE Cat. No …	6	2003

TITLE	CITED BY	YEAR
Robocup2003 cornell robocup documentation, mechanical group final documentation R D'Andrea RoboCup 2003	6	2003
Description of Cornell BigRed Small League RoboCup Team R Dandrea, JW Lee RobocCup-99 Team Descriptions. Small and Middle Leagues, 14-23	6	1999
Full information and full control in a behavioral context R D'Andrea, JC Doyle Proceedings of 35th IEEE Conference on Decision and Control 2, 1830-1835	6	1996
Volitant vehicle rotating about an axis and method for controlling the same R D'andrea, S Lupashin, MW Mueller, M Waibel US Patent 10,464,661	5	2019
Implementation of a parametrized infinite-horizon model predictive control scheme with stability guarantees M Muehlebach, C Sferrazza, R D'Andrea 2017 IEEE International Conference on Robotics and Automation (ICRA), 2723-2730	5	2017
Approximation of continuous-time infinite-horizon optimal control problems arising in model predictive control M Muehlebach, R D'Andrea 2016 IEEE 55th Conference on Decision and Control (CDC), 1464-1470	5	2016
Flying machine arena R d'Andrea, F Augugliaro, D Brescianini, L Gherardi, M Hehn, M Mueller, ... URL (16. april 2015): http://yingmachinearena. org/research 2 (2), 7.1	5	2014
Patch models and their applications to multivehicle command and control VG Rao, R D'Andrea IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics) 37 …	5	2007
RoboFlag--A Framework for Exploring Control, Planning, and Human Interface Issues Related to Coordinating Multiple Robots in a Realtime Dynamic Environment AI Chaudhry, MC Raffaello in Proc. of Intl. Conf. on Advanced Robotics	5	2003
Cornell Big Red: Small-Size-League Winner R D'Andrea, JW Lee AI magazine 21 (3), 41-41	5	2000
LMI approach to mixed performance objective controllers: application to Robust H2 Synthesis R D'Andrea CALIFORNIA INST OF TECH PASADENA CONTROL AND DYNAMICAL SYSTEMS	5	1995
Design, fabrication, modeling and control of a fabric-based spherical robotic arm M Hofer, R D'Andrea Mechatronics 68, 102369	4	2020

TITLE	CITED BY	YEAR
Towards vision-based robotic skins: a data-driven, multi-camera tactile sensor C Trueeb, C Sferrazza, R D'Andrea 2020 3rd IEEE International Conference on Soft Robotics (RoboSoft), 333-338	4	2020
Controlled flight of a multicopter experiencing a failure affecting an effector MW Mueller, S Lupashin, R D'Andrea, M Waibel US Patent App. 10/308,349	4 *	2019
Method and system for transporting inventory items PR Wurman, R D'Andrea, MT Barbehenn, AE Hoffman, MC Mountz US Patent App. 10/133,267	4 *	2018
Sensitivity of joint estimation in multi-agent iterative learning control A Schöllig, R D'Andrea IFAC Proceedings Volumes 44 (1), 1204-1212	4	2011
Motion design and learning of autonomous robots based on primitives and heuristic cost-to-go K Li, R D'Andrea Robotics and Autonomous Systems 56 (8), 658-669	4	2008
Distributed control design for spatially interconnected systems with robustness to small communication delays R Chandra, C Langbort, R D'Andrea Mathematical Theory of Networks and Systems	4	2004
The multidimensional system toolbox R D'Andrea, R Chandra Cornell University	4	2003
Distributed Control of Spatially Reversible Interconnected Systems with Boundary Conditions, submitted to SIAM Journal on Control and Optimization C Langbort, R D'Andrea	4	2003
Temporal discretization of spatially distributed systems R D'Andrea, C Beck, GE Dullerud Proceedings of the 38th IEEE Conference on Decision and Control (Cat. No …	4	1999
Generalizations of H-infinity optimization. Control of rotating stall R D'Andrea California Institute of Technology	4	1997
Active control of rotating stall using pulsed air injection: experimental results on a low-speed, axial ow compressor," R D'Andrea, RL Behnken, RM Murray SPIE Conference on Sensing, Actuation and Control in Aeropropulsion	4	1995
System having a plurality of unmanned aerial vehicles and a method of controlling a plurality of unmanned aerial vehicles F Augugliaro, M Waibel, M Hehn, R D'andrea, L Gherardi US Patent 10,795,352	3	2020

TITLE	CITED BY	YEAR
Method and system for transporting inventory items R D'andrea, PK Mansfield, MC Mountz, D Polic, PR Dingle US Patent 10,486,901	3	2019
Angle of Arrival Estimation based on Channel Impulse Response Measurements A Ledergerber, M Hamer, R D'Andrea 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems …	3	2019
State Estimate Recovery for Autonomous Quadcopters L Beffa, A Ledergerber, R D'Andrea 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems …	3	2018
Basis functions design for the approximation of constrained linear quadratic regulator problems encountered in model predictive control M Muehlebach, R D'Andrea 2017 IEEE 56th Annual Conference on Decision and Control (CDC), 6189-6196	3	2017
Control of a swinging juggling robot F Fontana, P Reist, R D'Andrea 2013 European Control Conference (ECC), 2317-2322	3	2013
A parameterized control methodology for a modular flying vehicle R Oung, MP Cruz, R D'Andrea 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems …	3	2012
Predictable motion in unpredictable domains: The spotlight tracking problem K Chung, V Rao, R D'Andrea AIAA Guidance, Navigation, and Control Conference and Exhibit, 6247	3	2006
Patch models and their applications to multi-vehicle control VG Rao, R D'Andrea 2006 American Control Conference, 6 pp.	3	2006
Phase transitions in the multi-vehicle task assignment problem MG Earl, R D'Andrea ASME 2005 International Mechanical Engineering Congress and Exposition, 161-168	3	2005
Exploiting symmetry for the distributed control of spatially interconnected systems B Recht, R D'Andrea 42nd IEEE International Conference on Decision and Control (IEEE Cat. No …	3	2003
Necessary and sufficient conditions for robust gain scheduling R D'Andrea California Institute of Technology	3	1996
An Annular Wing VTOL UAV: Flight Dynamics and Control R Gill, R D'Andrea Drones 4 (2), 14	2	2020

TITLE	CITED BY	YEAR
Computationally Efficient Force and Moment Models for Propellers in UAV Forward Flight Applications R Gill, R D'Andrea Drones 3 (4), 77	2	2019
Vision-Based Proprioceptive Sensing for Soft Inflatable Actuators P Werner, M Hofer, C Sferrazza, R D'Andrea arXiv preprint arXiv:1909.09096	2	2019
Design, modeling and control of a flying vehicle with a single moving part that can be positioned anywhere in space W Zhang, MW Mueller, R D'Andrea Mechatronics 61, 117-130	2	2019
A Method for Reducing the Complexity of Model Predictive Control in Robotics Applications M Muehlebach, R D'Andrea IEEE Robotics and Automation Letters 4 (3), 2516-2523	2	2019
Ultra-Wideband Angle of Arrival Estimation Based on Angle-Dependent Antenna Transfer Function A Ledergerber, R D'Andrea Sensors 19 (20), 4466	2	2019
Method and System for Transporting Inventory Items PR Wurman, R D'andrea, MT Barbehenn, AE Hoffman, MC Mountz US Patent App. 16/107,365	2	2018
Method and system for transporting inventory items PR Wurman, R D'andrea, MT Barbehenn, AE Hoffman, MC Mountz US Patent 10,067,501	~~2~~	2018
Method and system for transporting inventory items PR Wurman, R D'andrea, MT Barbehenn, AE Hoffman, MC Mountz US Patent 10,067,501	2	2018
Structured analysis of piecewise-linear interconnected systems JM Fowler, R D'Andrea International Journal of Robust and Nonlinear Control: IFAC-Affiliated …	2	2007
Trajectory Design of Autonomous Vehicles Based on Motion Primitives and Heuristic Cost-to-Go Functions K Li, R D'Andrea Proceedings of the 45th IEEE Conference on Decision and Control, 3345-3350	2	2006
Continuity and Monotonicity Properties of an Optimally Controlled Double Integrator with State and Input Constraints O Purwin, R D'Andrea Cornell University	2	2005
RoboFlag: Rules and regulation R D'Andrea	2	2002

TITLE	CITED BY	YEAR
Vision-Based Proprioceptive Sensing: Tip Position Estimation for a Soft Inflatable Bellow Actuator P Werner, M Hofer, C Sferrazza, R D’Andrea	2	
Sim-to-real for high-resolution optical tactile sensing: From images to 3D contact force distributions C Sferrazza, R D'Andrea arXiv preprint arXiv:2012.11295	1	2020
A Fast and Reliable Pick-and-Place Application with a Spherical Soft Robotic Arm J Zughaibi, M Hofer, R D'Andrea arXiv preprint arXiv:2011.04624	1	2020
Full-Order Solution to the Attitude Reset Problem for Kalman Filtering of Attitudes R Gill, MW Mueller, R D’Andrea Journal of Guidance, Control, and Dynamics 43 (7), 1232-1246	1	2020
Flying camera with string assembly for localization and interaction M Waibel, S Lupashin, M Hehn, R D'andrea US Patent 10,571,779	1	2020
Controlled flight of a multicopter experiencing a failure affecting an effector MW Mueller, S Lupashin, R D'andrea, M Waibel US Patent 10,562,611	1	2020
Iterative bias estimation for an ultra-wideband localization system B van der Heijden, A Ledergerber, R Gill, R D’Andrea IFAC-PapersOnLine 53 (2), 1391-1396	1	2020
Controlled flight of a multicopter experiencing a failure affecting an effector MW Mueller, S Lupashin, R D'andrea, M Waibel US Patent 10,308,349	1	2019
Flying camera with string assembly for localization and interaction M Waibel, S Lupashin, M Hehn, R D'andrea US Patent App. 15/695,295	~~1~~	2019
Flying camera with string assembly for localization and interaction M Waibel, S Lupashin, M Hehn, R D'andrea US Patent 10,168,601	1	2019
On the Approximation of Constrained Linear Quadratic Regulator Problems and their Application to Model Predictive Control-Supplementary Notes M Muehlebach, R D'Andrea arXiv preprint arXiv:1803.05510	1	2018
Accelerometer-Based Tilt Determination for Rigid Bodies With a Nonaccelerated Pivot Point M Muehlebach, R D'Andrea IEEE Transactions on Control Systems Technology, 1-15	1	2017

TITLE	CITED BY	YEAR
Approximation of continuous-time infinite-horizon optimal control problems arising in model predictive control-supplementary notes M Muehlebach, R D'Andrea arXiv preprint arXiv:1608.08823	1	2016
Addendum to: Event-based state estimation with variance-based triggering S Trimpe, R D’Andrea IDSC, ETH Zürich, Tech. Rep	1	2012
An Optimal Control Approach to Sensorimotor Parametrization M Sherback, R D'Andrea 2007 American Control Conference, 2036-2041	1	2007
Agent-Based Modeling with Polygon Primitives for Aerospace Applications S Goldfarb, VG Rao, R D’Andrea AIAA Modeling and Simulation Technologies Conference and Exhibit, 6469	1	2006
Real time, software control of spring suspended micro-electro-mechanical (MEM) devices for precision optical positioning applications KV Madanagopal, R D'Andrea, NC Tien IEEE/LEOS International Conference on Optical MEMs, 41-42	1	2002
Real-time visual perception for autonomous robotic soccer agents TC Karpati, R D’Andrea, JW Lee M. Eng. Design Report, EE Dept., Cornell University	1	1999
Controller synthesis for plants subject to linear time invariant full structured uncertainty R D'Andrea Proceedings of the 36th IEEE Conference on Decision and Control 3, 2708-2713	1	1997
Formation flight control and spatially interconnected systems R D’Andrea, J Fowler	1	
The Cornell RoboCup Robot Soccer Team R D’Andrea Series Editor, 793	1	
Controlled flight of a multicopter experiencing a failure affecting an effector MW Mueller, S Lupashin, R D'andrea, M Waibel US Patent 10,946,950		2021
Offset-free Model Predictive Control: A Ball Catching Application with a Spherical Soft Robotic Arm Y Huang, M Hofer, R D'Andrea arXiv preprint arXiv:2103.07379		2021
A Vision-based Sensing Approach for a Spherical Soft Robotic Arm M Hofer, C Sferrazza, R D’Andrea Frontiers in Robotics and AI 8, 8		2021

TITLE	CITED BY	YEAR
Distributed Estimation, Control and Coordination of Quadcopter Swarm Robots Z Jia, M Hamer, R D'Andrea arXiv preprint arXiv:2102.07107		2021
Human–Robot Collaboration: The Future of Smart Warehousing R D'Andrea Disrupting Logistics, 149-162		2021
Zero-shot sim-to-real transfer of tactile control policies for aggressive swing-up manipulation T Bi, C Sferrazza, R D'Andrea arXiv preprint arXiv:2101.02680		2021
Aerial vehicle M Hehn, M Waibel, L Gherardi, R D'Andrea US Patent App. 17/012,398		2020
System having a plurality of unmanned aerial vehicles and a method of controlling a plurality of unmanned aerial vehicles F Augugliaro, M Waibel, M Hehn, R D'Andrea, L Gherardi US Patent App. 17/011,759		2020
Methods and systems for scheduling the transmission of localization signals and operating self-localizing apparatus L Gherardi, R D'Andrea, MD Hamer, M Hehn, M Waibel US Patent App. 16/918,813		2020
Learning-based parametrized model predictive control for trajectory tracking C Sferrazza, M Muehlebach, R D'Andrea Optimal Control Applications and Methods 41 (6), 2225-2249		2020
FLYING CAMERA WITH STRING ASSEMBLY FOR LOCALIZATION AND INTERACTION M Waibel, S Lupashin, M Hehn, R D'andrea US Patent App. 16/793,570		2020
Methods and systems for scheduling the transmission of localization signals and operating self-localizing apparatus L Gherardi, R D'andrea, M Hehn, M Waibel US Patent 10,721,602		2020
Methods and systems for scheduling the transmission of localization signals and operating self-localizing apparatus L Gherardi, R D'andrea, M Hehn, M Waibel US Patent 10,440,533		2019
Methods and systems for scheduling the transmission of localization signals and operating self-localizing apparatus L Gherardi, R D'andrea, M Hehn, M Waibel US Patent 10,321,286		2019

TITLE	CITED BY	YEAR
Distributed localization systems and methods and self-localizing apparatus M Hehn, M Waibel, R D'andrea US Patent 10,302,737		2019
System and method for maneuvering a mobile drive unit R D'andrea US Patent App. 16/129,542		2019
Order through disorder P Reist, R D'Andrea Quantum of Disorder, 31-33		2015
2013 Index IEEE Robotics&Automation Magazine Vol. 20 N Abaid, D Abeywardena, E Aertbelien, J Agnus, G Alenya, A Alvarez, ... IEEE Robotics & Automation Magazine		2013
A Limiting Property of the Matrix Exponential S Trimpe, R D'Andrea IEEE Transactions on Automatic Control 59 (4), 1105-1110		2013
Flying with Payloads F Augugliaro, R D’Andrea		2013
Control of nonlinear systems with symmetries using chaos P Reist, R D'Andrea 2012 IEEE 51st IEEE Conference on Decision and Control (CDC), 997-1002		2012
Quadrocopter slalom learning AP Schoellig, FL Mueller, R D'Andrea Conference on Artificial Intelligence, Association of the Advancement of …		2012
The Cubli G Mohanarajah, M Merz, I Thommen, R D'Andrea 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems …		2012
Numerical models and controller design parameters for the balancing cube R D'Andrea, S Trimpe ETH Zurich		2012
Distributed Flight Array: A Software Perspective R Oung, R D’Andrea		2011
Asynchronous Extension of a Linear Distributed Averaging Algorithm M Kriegleder, R Oung, R D’Andrea Eidgenössische Technische Hochschule Zürich		2010
The potential for human flight performance augmentation G Robson, R D'Andrea Preprint submitted to 2010 IEEE International Conference on Robotics and …		2009
An Order-Based Approach to Mission-Oriented Autonomous Robot Control: Managing Complexity, Merging Multiple Plans, and Performance Analysis Given Partial Probabilistic Information K Li, R D'Andrea IFAC Proceedings Volumes 41 (2), 13707-13712		2008

TITLE	CITED BY	YEAR
Control of Air Vehicle Swarms R D'Andrea SIBLEY SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING ITHACA NY		2008
Abstraction-based command and control with patch models VG Rao, S Goldfarb, R D'Andrea Cooperative Control of Distributed Multi-Agent Systems, 409-432		2008
Learning through experience: Optimizing performance by repetition AP Schöllig, R D'Andrea 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)		2008
Videos of Trajectory Design Based on Motion Primitives: Direct Design and Learning K Li, R D'Andrea		2007
A Priority-Based Decision Model Demonstrated with Two-On-Two Robot Soccer K Li, O Purwin, R D'Andrea AAAI-07, Video Competition		2007
Path Planning by Negotiation for Decentralized Agents with Proof O Purwin, R D'Andrea		2006
Distributed sensing, actuation, communication, and control in emerging industrial applications R D'Andrea International Conference on Cellular Automata, 1-1		2006
Publisher's note iii D Kulic, EA Croft, O Purwin, R D'Andrea, E Maalouf, M Saad, H Saliah, ... Robotics and Autonomous Systems 54, 1049-1054		2006
Control, Estimation, and Optimization of Interconnected Systems: From Theory to Industrial Applications MR Jovanovic, C Langbort, B Bamieh, R D'Andrea, G Dullerud, ... Proceedings of the 44th IEEE Conference on Decision and Control, 24-26		2005
An affine approximation to the robust beamforming problem S Farahmand, ZQ Luo, GB Giannakis, R D'Andrea 1st IEEE International Workshop on Computational Advances in Multi-Sensor …		2005
Geometric Path Repair and Refinement in Hierarchical Motion Planning T Ho, VG Rao, R D'Andrea		2005
S. Kazadi, M. Chung, B. Lee and R. Cho On the dynamics of clustering systems Y Sun, N Xi, J Tan, T Kalmár-Nagy, R D'Andrea, P Ganguly, TD Barfoot, ... Robotics and Autonomous Systems 46, 265-266		2004
Robust and Optimal Control of Spatially Interconnected Systems, With Application to Coordinated Vehicle Control R D'Andrea CORNELL UNIV ITHACA NY DEPT OF MECHANICAL AND AEROSPACE ENGINEERING		2003

TITLE	CITED BY	YEAR
Discussion on 'Infinite Dimensional Backstepping-Style Feedback Transformations for a Heat Equation with Arbitrary Level of Instability'by A. Balogh and M. Krstic C Langbort, R D'Andréa, A Balogh, M Krstic European Journal of Control 2 (8), 176-177		2002
Synthesis Methods for Distributed and Time Varying Controlled Systems R D'Andrea, G Dullerud CORNELL UNIV ITHACA NY DEPT OF MECHANICAL AND AEROSPACE ENGINEERING		2001
Full information and full control in a behavioral setting R D'Andrea, JC Doyle Systems & control letters 41 (2), 85-93		2000
Satellite Attitude Control Using Magnetic Torquers, a Periodic Time-Varying Control Problem ML Psiaki, R D'Andrea CORNELL UNIV ITHACA NY		2000
Small-Size Robot (F180) League-Big Red: The Cornell Small League Robot Soccer Team R D'Andrea, JW Lee, A Hoffman, A Samad-Yahaja, LB Cremean, ... Lecture Notes in Computer Science 1856, 657-660		2000
Generalizations of H-infinity Optimization R D'Andrea		1996
Active control of rotating stall using pulsed-air injection: a parametric study on a low-speed axial flow compressor [2494-15] R D'Andrea, RL Behnken, RM Murray PROCEEDINGS-SPIE THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING, 152-152		1995
Optimal H~ System Design R D'Andrea, F Paganini IEEE CONFERENCE ON DECISION AND CONTROL 4 (33), 3679-3679		1994
Rapyuta: A Cloud Robotics Platform Mark G Mohanarajah, D Hunziker, R D'Andrea, M Waibel		
Tip Position Estimation of a Soft Inflatable Bellow Actuator: A Vision-Based Proprioceptive Sensing Approach M Hofer, P Werner, C Sferrazza, R D'Andrea		
Accurate estimation of the 3D contact force distribution with an optical tactile sensor–Live demonstration C Sferrazza, R D'Andrea		
Iterative Learning of Feed-Forward Corrections for High-Performance Quadrocopter Maneuvers AP Schoellig, FL Mueller, R D'Andrea		
The Cornell BigRed Team P Raghunathan, O Purwin, JW Lee, R D'Andrea		

TITLE	CITED BY	YEAR
A State-Space Approach to Control of Interconnected Systems C Langbort, R D'Andrea		
LMI approach to mixed performance objective controllers: application to Robust R D'Andrea Electrical Engineering 1000, 116-81		
SPECIAL SECTION ON CLOUD ROBOTICS AND AUTOMATION G Mohanarajah, V Usenko, M Singh, R D'Andrea, M Waibel, L Riazuelo, ...		
PREPRINTS: European Control Conference 2013, Zurich, Switzerland F Augugliaro, R D'Andrea		
Experimental Model-Based Control Design Using Multibody Codes R D'Andrea age 4, 1		
Encapsulated Path Planning for Abstraction-Based Vehicle Control VG Rao, T Wongpiromsarn, T Ho, K Chung, R D'Andrea		
Conference on Decision and Control Maui, Hawaii USA, December 2003 B Recht, R D'Andrea		
Patchworks: A Toolbox for Abstraction-Based Motion Planning in Multiagent Systems VG Rao, T Ho, T Wongpiromsarn, R D'Andrea		
WeP10-5 RS Chandra, R D'Andrea		

APPENDIX C

US010901404B2

(12) **United States Patent**
Stadie et al.

(10) **Patent No.: US 10,901,404 B2**
(45) **Date of Patent: Jan. 26, 2021**

(54) **METHODS, SYSTEMS AND APPARATUS FOR CONTROLLING MOVEMENT OF TRANSPORTING DEVICES**

(71) Applicant: **OCADO INNOVATION LIMITED**, Hatfield (GB)

(72) Inventors: **Robert Stadie**, Hatfield (GB); **Matthew Whelan**, Hatfield (GB); **Christopher Brett**, Hatfield (GB)

(73) Assignee: **OCADO INNOVATION LIMITED**, Herts (GB)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **16/575,906**

(22) Filed: **Sep. 19, 2019**

(65) **Prior Publication Data**

US 2020/0012268 A1 Jan. 9, 2020

Related U.S. Application Data

(60) Continuation of application No. 15/992,899, filed on May 30, 2018, now Pat. No. 10,474,141, which is a

(Continued)

(30) **Foreign Application Priority Data**

Jun. 3, 2014 (GB) 1409883.4

(51) **Int. Cl.**

G05B 19/418 (2006.01)
B65G 1/04 (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ***G05B 19/41895*** (2013.01); ***B60L 58/12*** (2019.02); ***B65G 1/0464*** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC G05B 19/41895
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,701,065 A * 2/1955 Bertel E04H 6/18
414/239
4,568,233 A 2/1986 Baker et al.

(Continued)

FOREIGN PATENT DOCUMENTS

CA 2831832 A1 10/2012
CN 1099988 C 1/2003

(Continued)

OTHER PUBLICATIONS

Office Action dated Sep. 26, 2019, by the U.S. Patent and Trademark Office in corresponding U.S. Appl. No. 15/993,208. (27 pages).

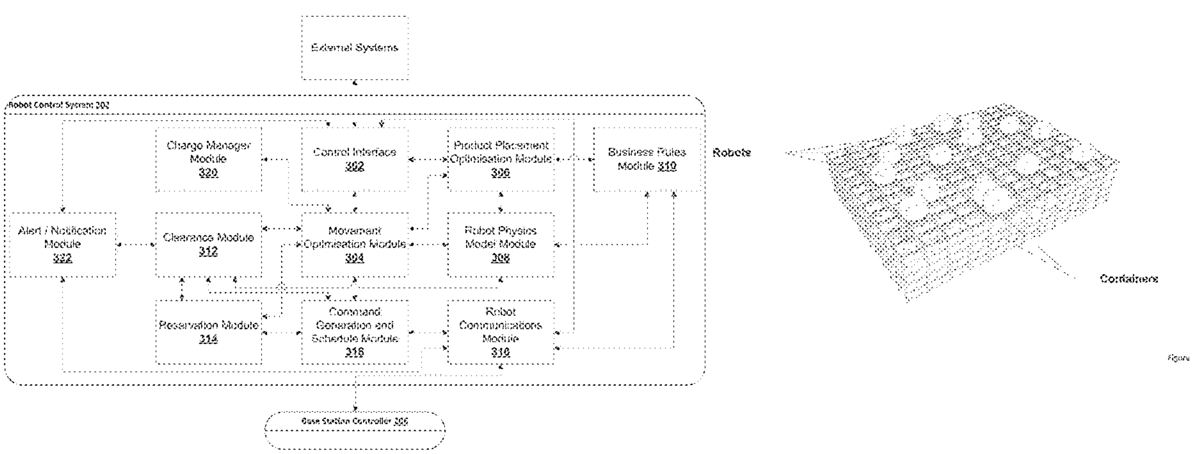
(Continued)

Primary Examiner — Thomas Randazzo
(74) *Attorney, Agent, or Firm* — Knobbe, Martens, Olson & Bear, LLP

(57) **ABSTRACT**

A system and method for controlling movement of transporting devices arranged to transport containers stored in stacks arranged in a facility having pathways arranged in a grid-like structure above the stacks, the transporting devices being configured to operate on the grid-like structure. A movement optimisation unit is configured to determine a route of a transporting device from one location on a grid-like structure to another location on the grid-like structure for each transporting device. A reservation unit is configured to reserve a path on the grid-like structure for each transporting device based on the determined route. A clearance unit is configured to provide clearance for each transporting device to traverse a portion of the reserved path.

20 Claims, 8 Drawing Sheets



Related U.S. Application Data

division of application No. 15/316,249, filed as application No. PCT/EP2015/062380 on Jun. 3, 2015, now Pat. No. 10,086,999.

(51) **Int. Cl.**

B65G 1/06	(2006.01)
G05D 1/02	(2020.01)
G06Q 10/04	(2012.01)
G06Q 50/28	(2012.01)
G06Q 10/08	(2012.01)
B65G 1/137	(2006.01)
B60L 58/12	(2019.01)

(52) **U.S. Cl.**

CPC ***B65G 1/0478*** (2013.01); ***B65G 1/065*** (2013.01); ***B65G 1/1378*** (2013.01); ***G05B 19/4189*** (2013.01); ***G05D 1/0255*** (2013.01); ***G05D 1/0289*** (2013.01); ***G05D 1/0297*** (2013.01); ***G06Q 10/04*** (2013.01); ***G06Q 10/08*** (2013.01); ***G06Q 10/087*** (2013.01); ***G06Q 50/28*** (2013.01); *B65G 1/0421* (2013.01); *B65G 1/1371* (2013.01); *G05D 2201/0216* (2013.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,918,607 A 4/1990 Wible
4,973,219 A 11/1990 Brickner et al.
5,179,329 A 1/1993 Nishikawa et al.
5,220,263 A 6/1993 Onishi et al.
5,511,923 A 4/1996 Dunstan
6,345,217 B1 2/2002 Zeitler et al.
6,589,001 B2 7/2003 Peltomaeki
6,654,662 B1 11/2003 Hognaland
6,748,292 B2 6/2004 Mountz
7,912,574 B2 3/2011 Wurman et al.
7,920,962 B2 4/2011 D'Andrea et al.
8,220,710 B2 7/2012 Hoffman et al.
8,381,982 B2 * 2/2013 Kunzig G05D 1/0291 235/462.08
8,433,469 B2 * 4/2013 Harvey G05D 1/0236 701/23
8,606,392 B2 12/2013 Wurman et al.
8,628,289 B1 1/2014 Benedict et al.
8,838,292 B2 * 9/2014 Palm G08G 1/164 701/2
8,873,829 B1 10/2014 Tyra et al.
9,002,506 B1 4/2015 Agarwal et al.
9,020,632 B2 4/2015 Naylor
9,020,682 B2 4/2015 Shitamoto et al.
9,087,314 B2 7/2015 Hoffman et al.
9,151,770 B2 * 10/2015 Reuteler G01N 35/1095
9,188,982 B2 * 11/2015 Thomson G05D 1/0212
9,205,978 B2 * 12/2015 Alba B66C 19/007
9,272,845 B2 3/2016 Honkanen et al.
9,280,154 B2 3/2016 Nagasawa
9,422,108 B2 8/2016 Hognaland
9,519,284 B2 * 12/2016 Wurman G05B 19/41895
9,598,232 B2 3/2017 Flick
9,598,239 B2 3/2017 Lert, Jr.
9,633,879 B2 * 4/2017 Ito H01L 21/67733
9,682,822 B2 * 6/2017 Lindbo B65G 1/0464
9,694,975 B2 7/2017 Lert et al.
9,723,832 B2 8/2017 Camenisch et al.
9,856,081 B2 * 1/2018 Alba B65G 63/004
9,886,036 B2 2/2018 Douglas et al.
10,067,501 B2 9/2018 Wurman et al.
10,133,267 B2 11/2018 Wurman et al.
10,251,388 B2 4/2019 Reuteler
2001/0038784 A1 11/2001 Peltomaki
2003/0222001 A1 12/2003 Christ
2004/0010337 A1 1/2004 Mountz et al.
2004/0067129 A1 4/2004 Krawczyk et al.
2004/0195310 A1 10/2004 Silverbrook et al.
2005/0220600 A1 10/2005 Baker et al.
2007/0293978 A1 12/2007 Wurman et al.
2008/0001372 A1 1/2008 Hoffman et al.
2009/0312864 A1 12/2009 Hanel
2010/0198391 A1 8/2010 Schaefer
2011/0060449 A1 3/2011 Wurman et al.
2011/0295413 A1 12/2011 Nara et al.
2011/0320376 A1 12/2011 Dearlove et al.
2012/0030070 A1 * 2/2012 Keller G06Q 10/087 705/28
2012/0123614 A1 * 5/2012 Laws G05D 1/0088 701/2
2012/0143427 A1 6/2012 Hoffman et al.
2012/0200259 A1 8/2012 Sullivan et al.
2012/0272500 A1 11/2012 Reuteler
2013/0011226 A1 1/2013 Camenisch et al.
2013/0085625 A1 4/2013 Wolfe et al.
2013/0138539 A1 5/2013 Delaney et al.
2013/0166062 A1 6/2013 Casey et al.
2013/0166134 A1 * 6/2013 Shitamoto G05D 1/0223 701/26
2013/0197719 A1 8/2013 Nagasawa
2013/0277425 A1 10/2013 Sharma et al.
2013/0302132 A1 11/2013 D'Andrea et al.
2014/0017052 A1 1/2014 Honkanen et al.
2014/0100690 A1 4/2014 Wurman et al.
2014/0100999 A1 4/2014 Mountz et al.
2014/0343717 A1 * 11/2014 Dorval G05D 1/00 700/217
2014/0365258 A1 12/2014 Vestal et al.
2015/0098775 A1 * 4/2015 Razumov B65G 1/0464 414/282
2015/0117995 A1 4/2015 D'Andrea et al.
2015/0127143 A1 * 5/2015 Lindbo B65G 1/0464 700/218
2015/0227140 A1 * 8/2015 Douglas G05D 1/0217 701/23
2015/0285644 A1 * 10/2015 Pfaff G05D 1/0088 701/25
2016/0060034 A1 * 3/2016 Tan B65G 1/0464 414/279
2016/0062357 A1 * 3/2016 Masaki B29J 9/1694 701/23
2016/0095309 A1 4/2016 Reuteler
2016/0272421 A1 * 9/2016 Hognaland B65G 1/06
2017/0038770 A1 2/2017 Inurman et al.
2017/0313517 A1 * 11/2017 Agarwal G06Q 10/087
2018/0020659 A1 1/2018 Camenisch et al.
2018/0075402 A1 3/2018 Stadie et al.
2018/0196413 A1 7/2018 Wurman et al.
2018/0276606 A1 9/2018 Stadie et al.
2018/0276607 A1 9/2018 Stadie et al.
2018/0276608 A1 9/2018 Stadie et al.
2018/0354893 A1 12/2018 Wurman et al.
2019/0064785 A1 2/2019 Wurman et al.

FOREIGN PATENT DOCUMENTS

CN 105246802 A 1/2016
EP 0767113 A2 4/1997
EP 0767113 A2 * 4/1997 .... B65G 1/0464
EP 1037828 A1 9/2000
EP 1138618 A1 * 10/2001 .... B65G 1/1378
EP 1138618 A1 10/2001
EP 1037828 B1 9/2003
EP 2006237 A1 12/2008
EP 1513747 B1 8/2009
EP 2508956 B1 10/2013
EP 3192753 A1 7/2017
FI 105668 B 9/2000
FI 109588 B 9/2002
FI 123447 B 5/2013
JP H 0881013 A 3/1996
JP 2001522342 A 11/2001
JP 2009513457 A 4/2009

(56) **References Cited**

FOREIGN PATENT DOCUMENTS

JP	2009541175 A		11/2009	
JP	2012197184 A		10/2012	
JP	2013156747 A		8/2013	
JP	5346127 B2		11/2013	
JP	5560978 B2		7/2014	
WO	9849075 A1		11/1998	
WO	WO-9849075 A1	*	11/1998	.... B65G 1/1371
WO	03095339 A1		11/2003	
WO	WO 2004/010337		1/2004	
WO	2007007354 A1		1/2007	
WO	2007011814 A2		1/2007	
WO	2007149712 A2		12/2007	
WO	2010118412 A1		10/2010	
WO	2011066856 A1		6/2011	
WO	2012127102 A1		9/2012	
WO	2013167907 A1		11/2013	
WO	WO-2013167907 A1	*	11/2013	.... B65G 1/137
WO	2014075937 A1		5/2014	
WO	2014145437 A1		9/2014	

OTHER PUBLICATIONS

Office Action dated Oct. 11, 2019, by the U.S. Patent and Trademark Office in corresponding U.S. Appl. No. 15/992,899. (6 pages).
Applicant-Initiated Interview Summary dated Apr. 10, 2020, by the U.S. Patent and Trademark Office in U.S. Appl. No. 15/993,097. (5 pages).
Office Action Summary dated Feb. 13, 2020, by the U.S. Patent and Trademark Office in U.S. Appl. No. 15/993,097. (31 pages).
Office Action Summary dated Mar. 25, 2020, by the U.S. Patent and Trademark Office in U.S. Appl. No. 15/993,208. (29 pages).
Notice of Allowance dated Jun. 19, 2019 issued in the corresponding U.S. Appl. No. 15/992,899, 12 pages.
Office Action dated Aug. 20, 2019 in the corresponding U.S. Appl. No. 15/993,097, 24 pages.
The Examiner's attention is directed to copending U.S. Appl. No. 15/993,097, filed May 30, 2018.
The Examiner's attention is directed to copending U.S. Appl. No. 15/993,208, filed May 30, 2018.
AutoStore Logistics-Technical Presentation, www.youtube.com/watch?v=iyVDMp2bL9c.
Swisslog AutoStore Review: An In-Depth Review of Automated Split Case Picking Technology for Distribution, MWPVL, Logistics Consultants, www.mwpvl.com/html/swisslog_autostore_review.html.
Bay, "Design of the Army-Ant Cooperative Lifting Robot," vol. 2, No. 1, 1995, pp. 5-7.
Lueth, et al., "Task Description Decomposition, and Allocation in a Distributed Autonomous Multi-Agent Robot System," vol. 3, 1994, pp. 1516-1523.
Mataric, et al., "Cooperative Multi-Robot Box-Pushing," pp. 556-561.
PCT/EP2015/062380, "International Search Report Received."
PCT/EP2015/062380, "Written Opinion Received."
Third Party Observation for PCT Application PCT/EP2015/062380, filed Jun. 3, 2016, in 34 pages.

* cited by examiner

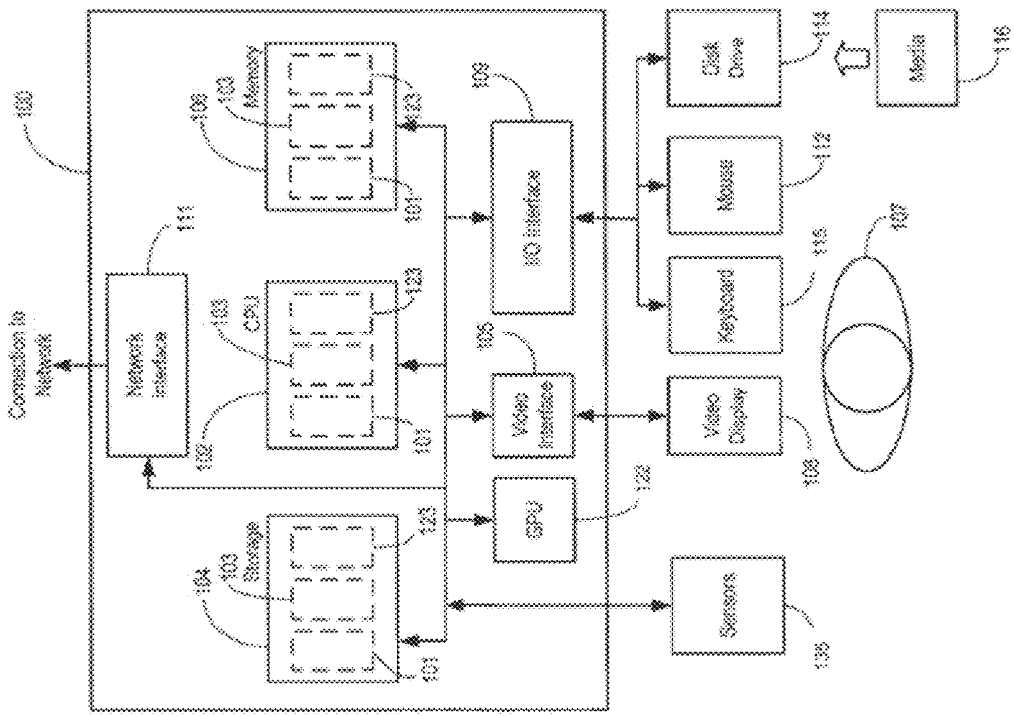

Memory
CPU
Storage
Network Interface
Connection to Network
I/O Interface
Video Interface
GPU
Disk Drive
Mouse
Keyboard
Video Display
Media
Sensors

FIG. 1

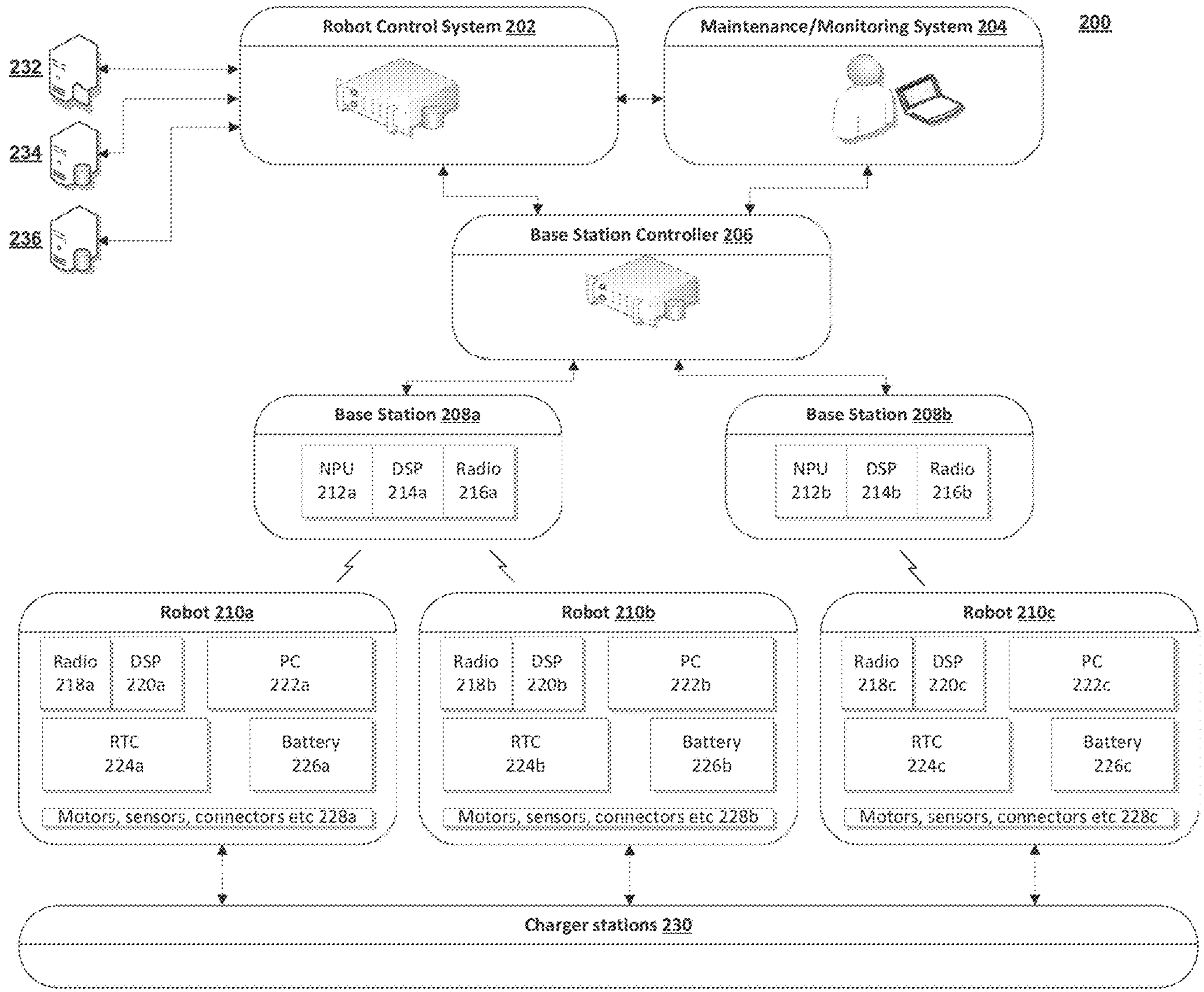

200
232
234
236
Robot Control System 202
Maintenance/Monitoring System 204
Base Station Controller 206
Base Station 208a
NPU 212a
DSP 214a
Radio 216a
Base Station 208b
NPU 212b
DSP 214b
Radio 216b
Robot 210a
Radio 218a
DSP 220a
PC 222a
RTC 224a
Battery 226a
Motors, sensors, connectors etc 228a
Robot 210b
Radio 218b
DSP 220b
PC 222b
RTC 224b
Battery 226b
Motors, sensors, connectors etc 228b
Robot 210c
Radio 218c
DSP 220c
PC 222c
RTC 224c
Battery 226c
Motors, sensors, connectors etc 228c
Charger stations 230

FIG. 2

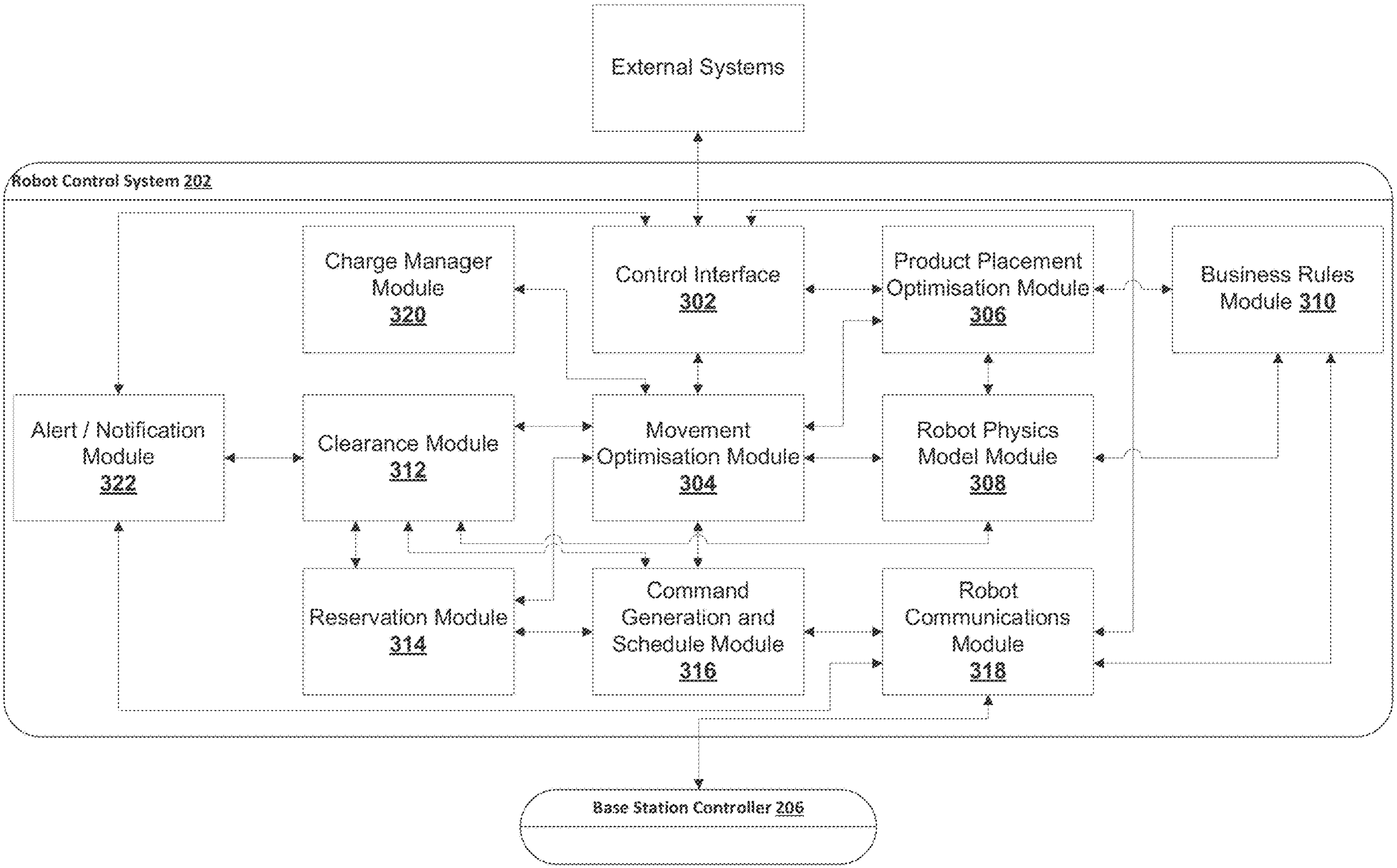

External Systems
Robot Control System 202
Charge Manager Module 320
Control Interface 302
Product Placement Optimisation Module 306
Business Rules Module 310
Alert / Notification Module 322
Clearance Module 312
Movement Optimisation Module 304
Robot Physics Model Module 308
Reservation Module 314
Command Generation and Schedule Module 316
Robot Communications Module 318
Base Station Controller 206

FIG. 3

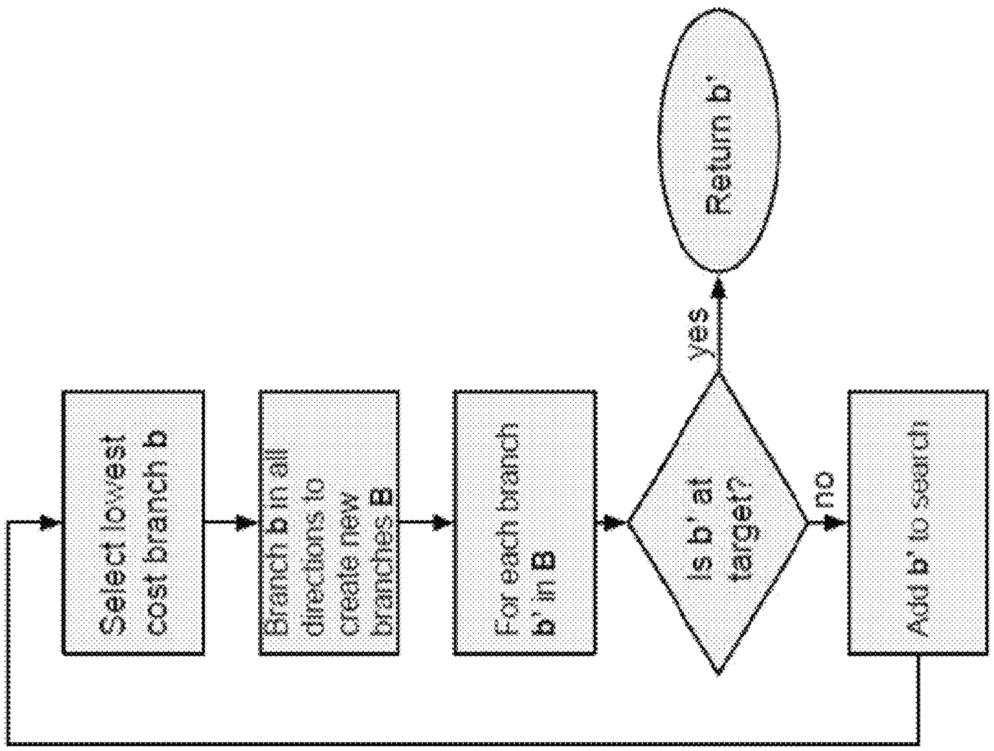

Select lowest cost branch b
Branch b in all directions to create new branches B
For each branch b' in B
Is b' at target?
yes
Return b'
no
Add b' to search

FIG. 4

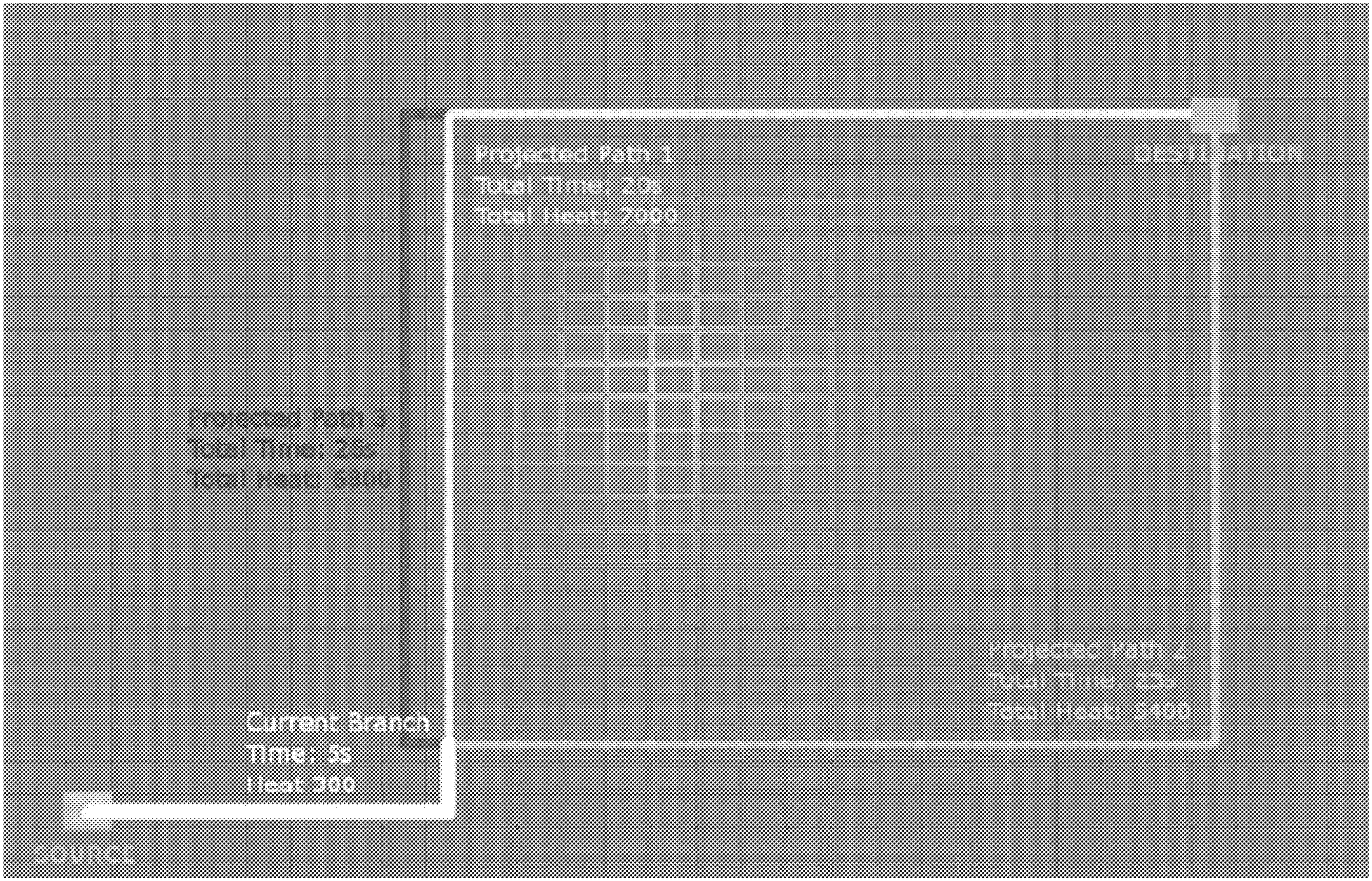

Projected Path 1
Total Time: 20s
Total Heat: 7000
Destination
Projected Path 3
Projected Path 2
Current Branch
Time: 5s
Heat: 300
Source

FIG. 5

			Path 1	Path 2	Path 3
		Total Time	20	23	26
		Total Heat	7000	5400	6800
	Coefficients			Total Path Costs	
x	C_t (= 2^x)	C_h (= 2^{-x})	Path 1	Path 2	Path 3
1	2	0.5	3540	2746	3452
2	4	0.25	1830	1442	1804
3	8	0.125	1035	859	1058
4	16	0.0625	757.5	705.5	841
5	32	0.03125	858.75	904.75	1044.5
6	64	0.015625	1389.375	1556.375	1770.25
7	128	0.007813	2614.688	2986.188	3381.125
8	256	0.003906	5147.344	5909.094	6682.563
9	512	0.001953	10253.67	11786.55	13325.28
10	1024	0.000977	20486.84	23557.27	26630.64

FIG. 6a

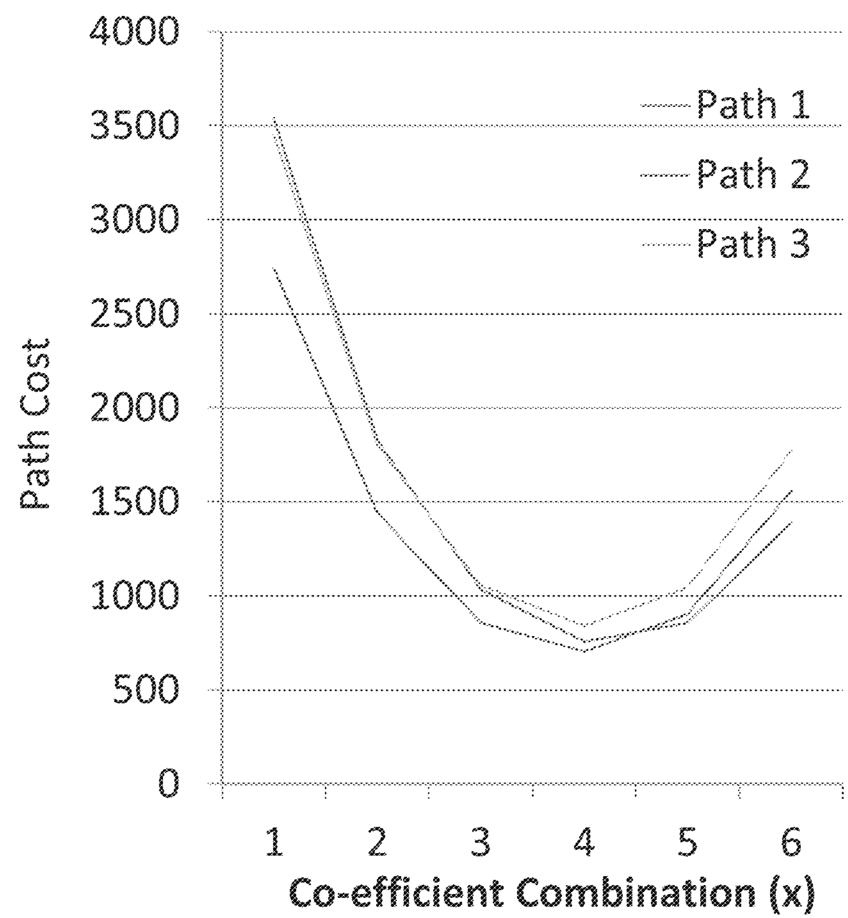


FIG. 6b

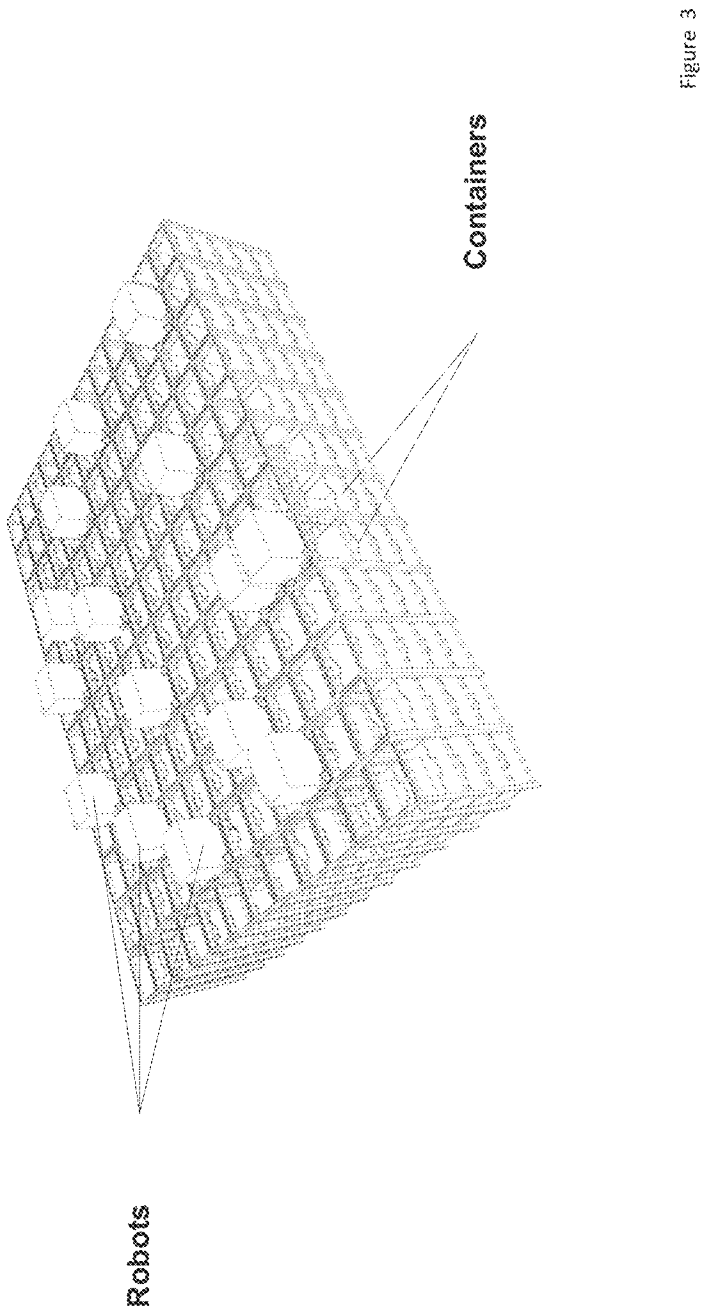


FIG. 7

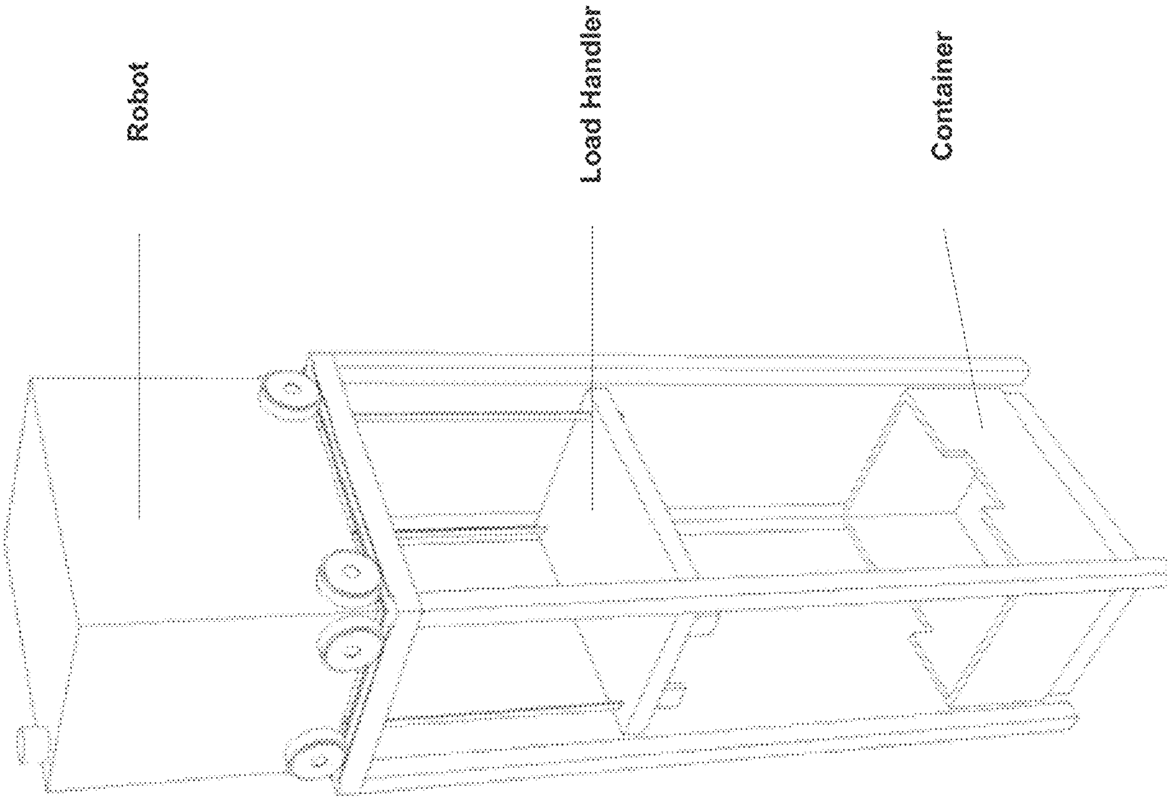


FIG. 8

METHODS, SYSTEMS AND APPARATUS FOR CONTROLLING MOVEMENT OF TRANSPORTING DEVICES

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation application of U.S. patent application Ser. No. 15/992,899 filed on May 30, 2018, which is a divisional application of U.S. patent application Ser. No. 15/316,249 filed on Dec. 5, 2016, which is a U.S. National Stage application based on International Patent Application No. PCT/EP2015/062380 filed on Jun. 3, 2015, which claims priority to British Patent Application No. 1409883.4 filed on Jun. 3, 2014, the entire content of all three of which is incorporated herein by reference.

SUMMARY OF THE INVENTION

The present invention relates to methods systems and apparatus for controlling movement of transporting devices. More specifically but not exclusively it relates to storage systems and methods for retrieving units from a storage system. In particular, but not exclusively, the invention further relates to systems and methods for coordinating and controlling product movement.

Certain commercial and industrial activities require systems that enable the storage and retrieval of a large number of different products.

One known system for the storage and retrieval of items in multiple product lines involves arranging storage bins or containers on rows of shelves arranged in aisles. Each bin or container holds one or more products of one or more product types. The aisles provide access between the rows of shelves, so that the required products can be retrieved by operatives or robots that circulate in the aisles.

It will be appreciated, however, that the need to provide aisle space to access the products means that the storage density of such systems is relatively low. In other words, the amount of space actually used for the storage of products is relatively small compared to the amount of space required for the storage system as a whole.

For example, online retail businesses selling multiple product lines, such as online grocers and supermarkets, require systems that are able to store tens or even hundreds of thousands of different product lines. The supply chains and warehouse operations of these businesses are highly dependent on their ability to organise, retrieve and return items to various containers.

In particular implementations of various warehouse and storage facility designs, containers may be stacked on top of one another and the stacks may be arranged in rows. The containers may then be accessed from above, removing the need for aisles between the rows and allowing more containers to be stored in a given volume or area.

In some of these implementations, the containers are accessed by one or more robotic or automated means, which navigate through a grid of pathways to access containers for a variety of different operations, such as moving a container from one location to another for handling, conducting operations upon a container, returning a container to a position in a warehouse, etc.

The co-ordination of the movement of the one or more robotic or otherwise automated means may be an important consideration in determining the overall efficiency and scalability of a system for storage and retrieval of a large number of different products.

In U.S. Pat. No. 6,654,662 and EP 1037828, a storage and retrieval system is described wherein "parallelepiped-shaped" containers are "deep-stacked and stock joined" in a vertical framework, forming several horizontal layers of containers whose positions at any time are random. A computer system continuously monitors and records the positions of the containers; desired containers are retrieved from the top of the framework, unwanted containers being moved, one at a time, and relocated to temporary locations until the desired container is retrieved, at which point the temporarily-relocated containers are returned to the same stack, and replaced in the same relative order; and the desired container is (eventually) returned to the top of original stack.

The system described in U.S. Pat. No. 6,654,662 and EP 1037828 has several horizontal coordinate forming layers of containers whose positions at any time are random. Further, temporarily-relocated containers are returned to the original stack, so that their relative order is retained, and wherein the desired container is returned to the top of the stack.

In contrast to the provided system, it may be advantageous to provide deliberate container placement that may be optimised in the horizontal and the vertical domains based on different criteria such as traffic flows, frequency of access (historic, current and forecast), specific container groupings, access time, fire-resistance and or other environmental partitions.

There is need, therefore, for systems and processes for coordinating and controlling product movement.

According to exemplary embodiments, a system is provided for controlling movement of transporting devices arranged to transport containers, the containers being stored in stacks arranged in a facility, the facility having pathways arranged in a grid-like structure above the stacks, the transporting devices being configured to operate on the grid-like structure, the system comprising: a movement optimisation unit configured to determine a route of a transporting device from one location on a grid-like structure to another location on the grid-like structure for each transporting device; a reservation unit configured to reserve a path on the grid-like structure for each transporting device based on the determined route, wherein the path reserved for each transporting device is provided such that no two transporting devices have locations on the grid-like structure which would cause transporting devices to overlap at a same time; and a clearance unit configured to provide clearance for each transporting device to traverse a portion of the reserved path.

A method is also disclosed for controlling movement of transporting devices arranged to transport containers, the containers being stored in stacks arranged in a facility, the facility having pathways arranged in a grid-like structure above the stacks, the transporting devices configured to operate on the grid-like structure, the method comprising: determining a route from one location on the grid-like structure to another location on the grid-like structure for each transporting device; reserving a path on the grid-like structure for each of the transporting devices based on the determined route, wherein the path reserved for each transporting device is provided such that no two transporting devices have locations on the grid-like structure which would cause transporting devices to overlap at a same time; and providing clearance for each transporting device to traverse a portion of the reserved path.

According to some embodiments of the invention, a system is provided for controlling the movement of one or more of transporting devices transporting a plurality of

objects and operating in a facility having a plurality of pathways, the system comprising:

one or more computers configured to execute computer instructions which when executed provide:

one or more utilities determining and reserving routes for moving the one or more transporting devices through the plurality of pathways; and

one or more utilities providing a clearance system for permitting or stopping movement of the one or more transporting devices to avoid collisions.

In some embodiments, the system further comprises one or more utilities configured to optimise the movement and actions of the one or more transporting devices through the plurality of pathways.

In some embodiments, the system further comprises one or more utilities configured to optimise the placement of the plurality of objects by the one or more transporting devices in the facility.

In some embodiments, the system further comprises one or more utilities that control movement or operations conducted within one or more workstations.

In some embodiments, the one or more utilities that optimise the movement and actions utilize pathfinding algorithms.

In some embodiments, the one or more utilities optimise the movement and actions using congestion mitigation techniques.

In some embodiments, the one or more utilities optimise the movement and actions using machine learning techniques.

In some embodiments, the one or more utilities optimise the placement of the plurality of objects within the facility, and update stock levels of the facility based on the placement of one or more of the plurality of objects within the facility.

In some embodiments, the one or more utilities control the movement of the one or more of transporting devices based at least on throughput of the one or more workstations.

In some embodiments, the one or more utilities provide a clearance system configured to be tolerant to missed communications with at least one of the one or more transporting devices.

In some embodiments, the one or more utilities determine and reserve routes, and instruct a plurality or transporting devices to cooperate in transporting one or more of the plurality of objects.

In some embodiments, the one or more utilities determine and reserve routes to move idle transporting devices from otherwise optimal routes for other transporting devices.

In some embodiments, one or more of the plurality of objects are stored within a plurality of containers.

In some embodiments, the facility stores the plurality of containers in a plurality of stacks.

In some embodiments, the one or more utilities determine and reserve routes for transporting one or more of the plurality of containers.

In some embodiments, the one or more utilities determine and reserve routes to control one or more of the plurality of transporting devices to retrieve one or more of the plurality of containers from within one or more of the plurality of stacks.

In some embodiments, retrieving the one or more containers from within the one or more stacks further requires moving one or more other containers in the stack prior to accessing the one or more containers for retrieval.

In some embodiments, moving the one or more other containers comprises placing each of the one or more other containers in an optimised position within the facility.

In some embodiments, the facility is divided into a plurality of sub-grids to reduce processing complexity.

In some embodiments, one or more control commands to control the movement of the plurality of transporting devices is provided to the plurality of transporting devices in advance of the movement of the plurality of transporting devices.

In various aspects, the disclosure herein provides methods, systems, and corresponding machine-executable coded instruction sets for coordinating and controlling product movement in at least a semi-automated order fulfillment system comprising a holding facility. In various aspects, the disclosure provides improvements in the coordination and control of the movement of robots handling a variety of goods in fulfillment of orders which, in some instances, may include a variety of items having different sizes, weights, fragilities and other characteristics.

In various embodiments of the above and other aspects, such a holding facility can include one or more storage apparatuses. In the same or other embodiments, at least a portion of the holding facility may be configured to move dynamically.

In the same or other embodiments, the holding facility may be shared between two or more workstations.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described with reference to the accompanying diagrammatic drawings, the drawings being to be exemplary and not limiting, and in which like references are intended to refer to like or corresponding parts.

FIG. **1** is an illustrative diagram providing a generic computer hardware and software implementation of certain aspects, as detailed in the description.

FIG. **2** provides a sample block diagram of the system, according to some embodiments of the invention.

FIG. **3** provides a sample block diagram of the robot control system in more detail, according to some embodiments of the invention.

FIG. **4** provides a sample workflow for a sample recursive path-finding algorithm, according to some embodiments of the invention.

FIG. **5** provides a sample heat map, according to some embodiments of the invention.

FIG. **6***a* provides a table demonstrating how a search branch's projected cost could change as a result of using different coefficients in the path search algorithm. These coefficients could be derived using refinement by a machine learning technique according to some embodiments of the invention.

FIG. **6***b* illustrates how the use of different cost coefficients demonstrated in FIG. **6***a* changes which branch will be selected by the next iteration of the search algorithm.

FIG. **7** provides a sample perspective view of a warehouse, according to some embodiments of the invention.

FIG. **8** provides a sample diagram of a robot with a winch and a container, according to some embodiments of the invention.

Preferred embodiments of methods, systems, and apparatus suitable for use in implementing the invention are described through reference to the drawings.

DETAILED DESCRIPTION OF THE INVENTION

Fully- and semi-automatic goods storage and retrieval systems, various aspects of which may sometimes be

referred to as "order fulfillment," "storage and retrieval," and/or "order picking" systems, can be implemented in a wide variety of types and forms. One manner of providing access to goods stored for fully- and/or semi-automatic retrieval, for example, comprises placement of goods, which may be of any desired type(s), in bins or other containers (hereinafter referred to generically as containers), and stacking and/or otherwise disposing the containers in racking or vertically in layers, such that individual containers may be accessible by wholly or partially-automated container retrieval systems.

In some embodiments, the systems may include systems beyond goods storage and retrieval, such as systems where goods are processed, repaired, manipulated, assembled, sorted, etc., and the movement of goods, products, parts, components, subcomponents is required, both within a facility and/or to other facilities or transportation.

For the purposes of this specification, a storage facility for the storage, retrieval, processing and/or fulfillment of orders, wherein access to such goods is provided by fully or semi-automatic retrieval, is referred to as a "hive". The "hive" may be comprised of a grid-like layout of the potential pathways for the movement of robotic elements or devices ("robot") to traverse and perform operations at various locations in the "hive" (referred to as the "grid").

The specification is not limited to only systems that have "hives", "grids", and/or "robots", but systems that broadly control and/or coordinate the movement and/or activities of a plurality of devices may also be contemplated. These devices may be configured for the transportation of various items, such as goods and/or products, and/or containers that may be empty and/or holding such goods and/or products. These devices may further be involved in the fulfillment of orders but may also be involved in any other type of activity, such as transporting containers to and from workstations, moving objects from source locations to target locations, etc.

As indicated, the devices may be robots, and the devices may be configured to move around a hive, and/or communicate with a control system to coordinate/receive instructions on their movement. In some embodiments, the devices may be configured to communicate amongst themselves, and/or coordinate movement amongst themselves. Accordingly, the devices may have various transporting means, communications means, powering means, processing means, processor means, sensor means, monitoring means, on-board workstations, electronic/physical storage means and/or lifting/transporting means (such as a winch, arms, etc.).

While the devices may be configured to receive instructions from the system, there may be situations where the devices lose communications with the system, have degraded communications pathways and/or do not receive communications from the system within a particular time frame.

In some embodiments, the devices may also be configured to communicate amongst each other, and/or sense the presence of each other. These communications and/or sensory inputs may be utilized, for example, in crowdsourcing information about the environment, providing redundant communications channels, verifying instructions, etc.

Fulfillment of orders may include various operations, such as, but not limited to: assembling orders where various products are purchased and aggregated for delivery to a customer, such as for a grocery chain; assembling products with various subcomponents; conducting various operations on products (such as soldering components together), sorting products, etc.

Orders may also be returned, for example, if an order is cancelled, a delivery fails, etc. In some scenarios, while an order is in the process of fulfillment within the hive, it may be cancelled and the product items may need to be returned. In some scenarios, the items may need to be placed again into containers, and the containers moved to various locations. In some scenarios, a workstation may need to conduct tasks to reject/rework products when an order is returned or cancelled.

Furthermore, as mentioned above, individual containers may be in vertical layers, and their locations in the "hive" may be indicated using co-ordinates in three dimensions to represent the robot or a container's position and a container depth (e.g. container at (X, Y, Z), depth W). In some embodiments, locations in the "hive" may be indicated in two dimensions to represent the robot or a container's position and a container depth (e.g. container at (X, Y), depth Z).

The "hive" itself may be a "dynamic" environment, in the sense that robots and workstation locations may be associated with different parts of the hive for engaging in actions. For example, robots may need to access a specific container in a specific location in the hive dimensions (e.g. container at (X, Y, Z), depth W) to fulfil a particular order or to store a product in the "hive". This involves movements of the robots along various possible paths, for example, along the top of the grid, and then accessing particular containers at selected depths of a stack.

The access of particular containers at selected depths of a stack may necessitate the movement of containers which may otherwise obstruct the ability to access a particular container (e.g. where the containers are stacked, a number of containers must be moved first to be able to access a container that is not at an accessible end of the stack). In some embodiments, it may be advantageous to have the system configured to provide for the evaluation and optimisation of a new position for every container that has to be removed to access a target container.

Containers moved off of a stack need not be moved back to their original stack.

One of the potential advantages is the ability to modify the distribution of containers such that the containers are located in more easily accessible or otherwise more convenient locations.

This may help maintain an optimal distribution of containers within the facility, for example, biasing containers that are expected to be in higher demand in more easily accessible locations, such as locations nearby or within workstations, to reduce travel distance.

FIG. **7** provides a sample perspective view of a warehouse, according to some embodiments of the invention.

Robots may have various shapes, sizes and configurations, and may have various communications means, sensors and tools. In some embodiments, each robot may be able to communicate with the control system through a set of frequency channels established through a set of base stations and base station controllers. Robots may utilize various tools to move and obtain containers from a stack, including, for example, a winch to carry a container.

FIG. **8** provides a sample diagram of a robot with a winch and a container, according to some embodiments of the invention.

The grid is not limited to rectangular grid elements and may be comprised of curved tracks, tracks up and down, etc. The grid pathways may have intersections and may be accessed by more than one robot.

Each grid may be segmented, physically or logically, into one or more sub-grids.

The grid may be comprised of one or more workstations. Workstations may be manual, semi-automated or fully automated, and may consist of locations or areas where operations are conducted within the hive, or operations are conducted in relation to the hive, containers or products, such as, moving products in or out of the hive, manufacturing products, assembling products, processing products to their components, providing staging locations to support other steps or operations, etc.

Workstations could include, for example, locations where items are moved from inbound carriers, locations where products have various operations conducted on them (e.g. assembly of components, painting, sorting, packaging, disassembly, reworking products, fixing packaging, replacing products in cancelled orders, rejecting returned products, disposing products), products are moved to outbound carriers, locations with capabilities for refrigeration, locations where components or objects are assembled, locations used for staging or pre-fetching products, locations where robots are repaired and maintained, locations where robots are charged, locations where workers "pick" products to be placed into containers, locations where workers "pick" products to be removed from containers in fulfillment of orders, bags are placed into containers, etc.

Where items/products are returned to the hive, the system may support and/or control the process of bringing back the product, reworking the product, and/or disposing the product if rejected. The scenario may, in some embodiments, involve processing the returned container (which may be a delivery tote or other object as well) at a workstation to determine whether it can be accepted back into the system, whether it needs reworking/repackaging, and/or whether the product should be disposed of instead (e.g. a perishable product has expired).

Workstations may have one or more workers or robots present to conduct various tasks, such as picking items for fulfillment of orders.

In some embodiments, workstations may also be stations with conveyors, refrigerators, various tooling technologies and/or other technology to manipulate, paint, fasten, repair, freeze, heat, expose to chemicals, refrigerate, filter, assemble, disassemble, sort, package, scan, test, transport, store or process goods, containers, etc.

The workstations may have their own pathways within the facility, share pathways with the facility, etc. The workstations may also have various input and output pathways or other types of entry/egress points within the facility.

In some embodiments, the workstations communicate with one or more warehouse management systems to provide information and data related to the status of the workstation, workflow, required containers, issues, status of products held or otherwise manipulated (e.g. sub-components being assembled together), etc.

Upon receipt of an order from a customer for multiple items stored in a storage and retrieval system, fully or semi-automated container handlers may retrieve storage containers containing relevant items from a grid, racking, or other ordered arrangement of storage containers, and deliver them to one or more workstations.

At the workstations, items may be removed from the storage containers and placed in an intermediate holding facility before being picked into delivery containers.

As indicated throughout this specification, it may be advantageous to have a distribution of containers such that containers that are likely inputs for certain workstations are located close in proximity to those workstations.

The picking of items from containers may be done manually by human pickers, or be conducted in a semi-automated or fully-automated manner with the assistance or participation by various mechanical or robotic elements.

Where individual containers are stacked vertically in layers, accessing a container that is not at the top layer may require a further set of operations to move containers stored at layers above the desired container prior to being able to access the desired container. For example, if a desired container is one level below the top layer, the container residing within the top layer may need to be moved to another location prior to accessing the desired container. As indicated throughout this specification, it may be advantageous to have a distribution of containers such that containers holding items in greater demand are biased towards the more easily accessible positions (e.g. if a vertical stack of containers, the uppermost levels). In some embodiments, an optimisation module provides an optimal location for these containers to be positioned.

In a typical commodities picking operation adapted for handling a large variety of items, such as a grocery order processing system, it is sometimes found that a wide range of items of various sizes, shapes, weights, and other characteristics must be handled or otherwise accommodated, and that these items may need to be moved around a facility to various stations for various operations to be conducted, during the fulfillment of one or more order(s). Depending on the size, organisation and arrangement of the facility, the movement of these items may be advantageously optimised so that items are moved efficiently, collisions are avoided and dependencies are resolved (e.g. objects are picked and unloaded in a proper order).

The various actions involved in these working groups such as placement of items in different types of containers, storage of containers within the hive, and sorting/delivery as described can result in various movements of the containers, including within the hive, but also placement of containers in different locations. These actions may include inbound/outbound activity to the hive (e.g. bringing items to and from a warehouse), and may also include associated sorting/delivery systems such as management of conveying product off vehicles for storing/delivery, and also conveying onto vehicles for order fulfilment.

In other embodiments of the invention, the workstations may be utilized to provide other types of item handling or container handling, such as workstations where actions are performed on items (e.g. assembly, disassembly, modification, sorting, drying, freezing, testing, chemical exposure, physical manipulation, fastening, repair, printing, painting, cutting, packaging, storage, processing, welding, tempering, reprocessing). These workstations may be manual, semi-automated, or automated and have various parameters associated with their operation or performance, such as throughput, required inputs, required outputs, load balancing, required delays (e.g. drying time), etc.

The various movements of the robots, placement of containers/objects, and control over selecting when to remove product from containers may be controlled and optimised by one or more control systems. This control may include the implementation of various strategies, including, for example:

- The central management of one or more robots;
- Managing the robots not only to retrieve containers for processing, but also to "pre-fetch" containers to more convenient locations, for example, locations close to or within workstations;
- Path optimisation through the application of one or more path finding algorithms (e.g. branch and bound techniques);
- Path optimisation through the application of one or more heuristic techniques to the one or more path finding algorithms (e.g. projected lowest cost, where in one embodiment of the invention, cost may be calculated as a function of total time to target, and total "accumulated heat" for congestion mitigation on the grid when viewed as a whole);
- Scheduling/pre-processing movement pathways in advance;
- Conducting simulations to determine optimal depth of analysis in scheduling/pre-processing movement pathways;
- Application of machine learning techniques to optimise exponents and coefficients applied to the cost functions of one or more algorithms. In some embodiments, this may include path finding, container placement and workstation load-balancing algorithms;
- A just-in-time robot path conflict resolution system;
- The subdivision of the robot population into separate control groups each containing one or more robots;
- Container location optimisation through various means, such as the application of a scored selection algorithm using weighted cost coefficients;
- Optimisation of the allocation of work to workstations;
- Pre-processing of tasks and actions to schedule future tasks and actions.

In an example environment where one or more robots are used for the fully or semi-automated retrieval, storage and movement of objects, the warehouse may first have to decide how to distribute the container loads between different robots or groups of robots.

For example, the allocation of tasks across various groups of robots and pick stations may be optimised depending on the particular layout of a warehouse, the placement of items, particular characteristics of goods (e.g. the item is expiring or is potentially dangerous) and the workflow ordering.

For example, it may be desirable to have a system that intelligently compares potential paths for a robot to take to its destination, taking into consideration, among others, the potential congestion along that path, the time required to complete operations, the potential for collisions, the objects held in the inventory of a particular robot, predicted future operations and the characteristics of a particular robot (e.g. battery levels, service issues).

It may further be desirable to have a system that intelligently adapts to various conditions in the "hive", such as idle robots that may hinder or block the path of a robot, obstacles, or other robots reserving paths that a particular robot is seeking to traverse.

It may further be desirable to have a system that intelligently positions containers based on an algorithm to bias the system towards a distribution of containers that aids in the efficient retrieval of items (e.g. containers with items of high-demand SKUs are kept near the top and near their workstations for ease of access).

These are non-limiting examples, and any optimisation methods, arrangements or considerations may be implemented.

Referring to FIG. **2**, a schematic diagram is provided of sample fully- and semi-automatic goods storage and retrieval systems, according to some embodiments of the invention. FIG. **2** is provided at a high level, illustrating an example implementation. Various implementations of the system **200** may involve more or less components and FIG. **2** is merely provided as an example.

The system **200** is comprised of a robot control system **202**; a maintenance/monitoring system **204**; a base station controller **206**; one or more base stations **208***a* and **208***b*; one or more robots **210***a*, **210***b* and **210***c*, and one or more charger stations **230**. While only two base stations **208***a* and **208***b*, and three robots **210***a*, **210***b* and **210***c* are illustrated, it should be understood that that there may be more, or less robots and base stations in other embodiments of the system.

There may be one or more warehouse management systems (WMS) **232**, order management systems **234** and one or more information management systems **236**.

The warehouse management systems **232** may contain information such as items required for an order, SKU#s in the warehouse, expected/predicted orders, items missing on orders, when an order is to be loaded on a transporter, expiry dates on items, what items are in which container, whether items are fragile or big and bulky, etc.

In some embodiments, the warehouse management systems **232** may be in communication with the workstations and may also contain information related to the operation of the workstations, such as the status of the workstation, what products and/or what containers the workstation is required to receive at particular times, what products and/or containers the workstation will be required to have moved to another location at particular times, the expected workflow for operations at the workstation, the number of robots currently waiting to bring containers to a workstation, etc.

The robot control system **202** may be configured to control the navigation/routing of robots, including, but not limited to, moving from one location to another, collision avoidance, optimisation of movement paths, control of activities to be performed, etc. The robot control system **202** may be implemented using one or more servers, each containing one or more processors configured based upon instructions stored upon one or more non-transitory computer-readable storage media. The robot control system **202** may be configured to send control messages to one or more robots, receive one or more updates from one or more robots, and communicate with one or more robots using a real or near-real time protocol. The robot control system **202** may receive information indicating robot location and availability from one or more base stations **208***a* and **208***b*. The robot control system **202** may be configured to keep track of the number of robots available, the status of one or more robots, the location of one or more robots and/or their current instruction sets. The robot control system **202** may also be configured to process and/or send control messages to the one or more robots in anticipation of future movements, potentially reducing the processor load, and also proactively managing the traffic load with respect to the communications links. Such an implementation could be advantageous in light of complex algorithms in use by the robot control system **202** in determining optimal pathways, calculating optimal locations for containers and/or determining reservations and/or clearances.

In some embodiments, the servers may utilize a 'cloud computing' type platform for distributed computing. A cloud-based implementation may provide one or more advantages including: openness, flexibility, and extendibility; manageable centrally; reliability; scalability; being opti-

mized for computing resources; having an ability to aggregate information across a number of users; and ability to connect across a number of users and find matching subgroups of interest. While embodiments and implementations of the present invention may be discussed in particular non-limiting examples with respect to use of the cloud to implement aspects of the system platform, a local server, a single remote server, a software as a service platform, or any other computing device may be used instead of the cloud.

In some embodiments, the movement optimisation module may utilize one or more control groups to segregate robots into the one or more groups. The use of control groups for large grids may provide certain advantages, such as the ability to maintain operation of a very large grid whenever real-time computation cannot keep up with re-planning after a control anomaly such as when (i) wireless communication link drops more sequential packets than allowed for in planning; (ii) one or more robots fail; (iii) one or more robots operate outside the pre-determined tolerance on performance.

A control stop message may be broadcasted to the robots in a particular "control group"; potential benefits from broadcasting messages as opposed to sending individual messages may include improved communications through the use of multiple transmission slots and a potentially higher signal to noise ratio.

In some embodiments, the robot control system **202** may be configured to dynamically assign robots to different "control areas" as they move across the grid.

The maintenance/monitoring system (MMS) **204** may be configured to provide monitoring functions, including receiving alerts from one or more robots or one or more base stations, establishing connections to query robots. The MMS **204** may also provide an interface for the configuration of monitoring functions. The MMS **204** may interact with the robot control system **202** to indicate when certain robots should be recalled.

The base station controller **206** may store master routing information to map robots, base stations, and grids. In some embodiments, there may be one base station controller **206** per warehouse, but in other embodiments of the invention, there may be a plurality of base station controllers. The base station controller **206** may be designed to provide high availability. The base station controller may be configured to manage dynamic frequency selection and frequency allocation of the one or more base stations **208***a* and **208***b*.

The base stations **208***a* and **208***b* may be organised as a pool of base stations, which may then be configured to be active, on standby or to monitor the system. Messages may be routed through a variety of communications means to/from robots. The communications means may be any communications means, in some embodiments, the communications means may be a radio frequency link such as those falling under wireless standard 802.11. The base stations **208***a* and **208***b* may further include processing units **212***a*, **212***b*, digital signal processors **214***a*, **214***b*, and radios **216***a*, **216***b*.

The one or more robots **210***a*, **210***b*, and **210***c* may be configured to move around the grid and to perform operations. Operations may include moving a container from one stack to another, going to a charging station to recharge, etc. The one or more robots may be assigned to communicate with the one or more base stations **208***a* and **208***b*.

The one or more robots **210***a*, **210***b*, and **210***c* may not all be the same type of robot. There may be different robots with various shapes, designs and purposes, for example, there may be a robot with a footprint of a single grid position which winches containers for internal stowage, a cantilever robot, a bridge robot, a recovery robot, etc.

In some embodiments, the one or more robots **210***a*, **210***b* and **210***c* have winches on them which may be used to retain a container for movement from one position on the grid to another.

The robots **210***a*, **210***b* and **210***c* may have, respectively, radios **218***a*, **218***b*, **218***c*, digital signal processors **220***a*, **220***b*, **220***c*, processors **222***a*, **222***b*, **222***c*, real time controllers **224***a*, **224***b*, **224***c*, batteries **226***a*, **226***b*, **226***c* and motors, sensors, connectors, etc., **228***a*, **228***b*, **228***c*.

The one or more charger stations **230** may be configured to provide power to charge batteries on the one or more robots **210***a*, **210***b* and **210***c*. The one or more charger stations **230** may further be configured to provide high speed, wired data access to the one or more robots, and several charge stations may be placed around the grid for use by the one or more robots **210***a*, **210***b* and **210***c*.

Referring to FIG. **3**, a block diagram is provided of the control system **202**, according to some embodiments of the invention. The block diagram is provided for illustrative purposes to identify some of the components of control system **202** in more detail, however, not every module or interface identified may be required and, in various embodiments, more or fewer modules may be included.

The control system **202** may be configured to evaluate how to improve work allocations, movements of product and placement of product. According to various embodiments of the invention, optimisations may be run in real time, while others are run, for example, periodically during down time or less active times.

The control system **202** may be configured to schedule when specific types of movements should happen and in what order they should occur, depending on the application of various business rules, indicating priority, etc. The control system **202** is configured to determine both inbound and outbound factors in making decisions even relative to product placement for example. For example, the control system **202** may act on estimated delivery location of product supply, and estimated outbound delivery of product. The control system may make decisions, and may send signals for execution by an automatic system, and/or may allocate tasks efficiently to humans (pickers, loaders etc.).

The control system **202** may determine that one or more robots or one or more pickers should conduct one or more actions in the fulfillment of an order or for any other purpose. The action of the one or more robots may require the robots to traverse the grid, and/or to conduct actions, such as retrieving a container.

The control system **202** may be configured to analyze various pathways in the grid to determine one or more paths that may potentially be preferential relative to other pathways, given a set of constraints and conditions. These preferential pathways may then be provided, one-time, periodically and/or dynamically to the robots to control their movements throughout the grid.

A path may be preferential for a number of reasons, including, but not limited to: less distance travelled, greater expected average velocity of robot, lower probability of encountering traffic (i.e. congestion), less total time required, lower probability of collision, less power used, ease of switching to alternate pathways, ability to avoid obstacles (e.g. a broken robot, a dropped item, a broken path, a part of the path is under repair).

The control system **202** may use various algorithms to identify, design and/or control the movement of various robots it is connected to. In some embodiments, the control

system is implemented using one or more servers, each containing one or more processors configured to perform one or more sets of instructions stored upon one or more non-transitory computer readable media. Potential advantages for computer implementation include, but are not limited to, scalability, ability to handle large amounts of processing and computational complexity, increased reaction speed, ability to make decisions quickly, ability to conduct complex statistical analysis, ability to conduct machine learning, among others.

These algorithms are discussed more at depth further in the specification, and sample path-finding algorithms and heuristic approaches are provided, according to some embodiments of the invention.

Constraints may include the current layout of the grid, the physics of the robot (e.g. maximum velocity, turning radius, turning speed, maximum acceleration, maximum deceleration), congestion (e.g. expected traffic load at a certain pathway or intersection), established 'highways', impact of objects being carried by the robot (e.g. big, bulky, or fragile objects), robot status and condition (including battery condition, damage, maintenance issues), and station status (e.g. the destination station is full or temporarily blocked).

The control system **202** may be a real or near-real time control system (controlling the actions of the various units including robots and optionally the associated other units involved such as conveyors, pickers, humans, etc.). The control system **202** may be comprised of one or more modules. The one or more modules may include a control interface **302**, a movement optimisation module **304**, a product placement optimisation module **306**, a robot physics model module **308**, a business rules module **310**, a clearance module **312**, a reservation module **314**, a command generation and scheduler module **316**, a robot communications module **318**, a charge manager module **320** and an alert/notification module **322**. These modules may be implemented in various ways, in some embodiments they are implemented as applications stored as instructions on one or more computer-readable media to be performed by one or more processors.

The control system **202** may provide real or near-real time control of the allocation of work, workstation operations, the movement of robots and/or the placement of containers, according to some embodiments of the invention. The allocation of work, movement and placement of containers may be precipitated by actions as relevant to activities within a warehouse, such as the fulfillment of orders, the redistribution of containers to more easily accessible positions, estimated dispatch sequences, maintenance operations, workstation operations, anticipation of future orders, etc.

The control interface **302** provides an interface for various external systems to provide directions and information into the control system **202**. The control interface **302** may, in various embodiments, provide interfaces for human users and/or interfaces for interfacing with various machines and systems.

Interfaces for humans may include, for example, keyboards, visual displays, command prompts, etc.

Interfaces for machines and systems may include application programmable interfaces (APIs), implemented using different specifications, including, but not limited to, simple access object protocol (SOAP) and representational state transfer (REST) services, and/or interfaces written in various programming languages. The control interface **302** may interact with various external databases, including but not limited to various warehouse management systems and order management systems; and also may receive information from the various robots (e.g. a robot is malfunctioning, a robot requires charging, a robot is en route to the destination, a robot has encountered an unexpected obstacle, etc.).

The control interface **302** may also receive and transmit information to and from the warehouse management system (WMS) relevant to the control and movement of robots and containers. Such information may include, but is not limited to, grid location and sizing, the establishment of sub-grids, master records of inventory and orders, locations of workstations, parameters related to workstations, and/or also the dispatch sequence (e.g. when orders need to go out). As actions are performed, containers brought to workstations, workstation operations completed, delivery totes filled, etc., the control interface **302** may provide updates to the WMS. In some embodiments, there is a confirmation process between the WMS and the control interface **302**. These updates to the WMS may include, for example, updated stock levels related to particular SKU#s, updated container positions, updated object positions within containers, updated facility conditions, etc.

In some embodiments of the system, in addition to the WMS, there may also be a separate order system that contains and provides information regarding various orders entering the system, the fulfillment of orders, workstation operations, upcoming orders and predicted orders.

The control interface **302** may also receive commands to stop the operation of a particular robot, a group of robots or all of the robots (e.g. in the event of a malfunction, an emergency, etc.).

The movement optimisation module **304** may be configured to optimise the movement of robots through applying various algorithms to determine potentially advantageous routes from one location to another. The potential advantages may include shorter distance travelled, lower likelihood of encountering congestion, shorter time required, lower power consumption, co-ordination with movements of other robots, routing around obstacles such as broken robots or broken areas of track, co-ordination with various workstation operations, etc.

The movement optimisation module **304** may be configured to provide work allocation, planning and scheduling functions, including developing a set of tasks and then selecting which pick station or robot should conduct which task. For example, this may be based upon where a robot or a pick station is located, the particular capabilities of the robot or pick station, etc. Further, the particular permutations and set of actions required to fulfill a particular order are determined and actions/tasks are developed for one or more robots and or one or more pick stations. Functions may include, among others, delivering empty containers to inbound stations, placing containers loaded with goods around the warehouse, bringing containers to pick stations or other areas, moving containers from one location in the warehouse to another, etc.

The movement optimisation module **304** may be configured to interact with the product placement optimisation module **306** in determining a set of potentially advantageous locations to place an object. For example, given that a container containing items of a particular SKU# that is required at a high frequency, the product placement optimisation module **306** may indicate that it should be placed at a certain location in a certain stack that is more accessible for retrieval. Conversely, if a container contains items of a particular SKU# that is required at a low frequency, the

product may be determined to be placed at a lower depth within a less easily accessible grid location.

In optimizing movement, the movement optimisation module **304** may be configured to consider various factors involved in both movement and the performance of an operation, such as the expected time required to get to a particular location, how deep the container is within a stack, how long it would take to dig a container out of a stack, the various operations necessary to move containers located above to other locations, etc.

The movement optimisation module **304** may also be provided a set of inputs from the robot physics model module **308**, which may communicate a set of constraints on the movement of the robot depending on various factors (e.g. the robot may only move at 50% of the maximum velocity as the robot is currently carrying delicate objects). The movement optimisation module **304** may coordinate the movement of boxes into the grid, out of the grid and within the grid.

In some embodiments, the movement optimisation module **304** may dynamically recalculate preferential paths during the course of a robot's journey to potentially determine an updated set of paths as conditions and constraints change over time.

In some embodiments, the grid may be pre-processed by the movement optimisation module **304** to potentially increase processing speed and/or reduce processing load. Other methods of reducing processing load are also contemplated, such as reducing the depth/breadth of searching, dividing the grid into sub-grids, distributed processing, caching future routes, computationally simplifying the grid (e.g. reducing the number of nodes under analysis), reducing path re-calculation, etc.

In some embodiments, the movement optimisation module **304** may divide a grid into a plurality of smaller sub-grids for analysis. Such division may ease demands on processing power, which may be particularly useful if grid sizes are very large; for example, a 1000×1000 grid may be broken into 100 100×100 grids and each grid analyzed separately. This may be further useful if the system is attempting to control a very large number of robots or take into consideration a large number of conditions.

The movement optimisation module **304** may also interact with the clearance module **312** and the reservation module **314** in determining whether the navigation of a proposed pathway will encounter issues involving the clearances and reservations of other robots and also determining pathways that may reduce the chances of encountering these issues.

Where a desired container is located within a stack at various depths within the stack, the movement optimisation module **304** may be required to control one or more robots in the movement of containers off the stack so that the desired container is accessible. The movement optimisation module **304** may coordinate movement across one or more robots such that the one or more robots cooperate in moving containers off the stack.

In some embodiments, the movement optimisation module **304**, it may not be necessary or even desired to replace the containers on the stack, rather, containers that have been moved off of the stack may have an optimal position determined by the product placement optimisation module **306**, and may be moved there by the one or more robots. A potential advantage of such an embodiment is that increased efficiency may be found when containers are not replaced in their original position but rather placed in a more optimal position.

In some embodiments, the clearance module **312**, the reservation module **314** and the movement optimisation module **304** are utilized together as a path conflict resolver, wherein a movement optimisation module **304** develops a path and then reserves the path using the reservation module **314**, and the clearance module **312** provides a just-in-time approach to determining priority when robots are engaged in potentially conflicting paths.

In some embodiments, the movement optimisation module **304** is configured to account for situations where a robot is attempting to take a container to a full station. In this situation, the movement optimisation module **304** is configured to instruct the robot to take the container nearby to be held by the robot until the station can accept the container. When the station can accept the container, it is dropped off. In these embodiments, held containers may be dropped off in priority order.

In some embodiments, if a station becomes free for drop off before the held container arrives at its holding location, the movement optimisation module **304** will re-plan to drop off the container directly, without holding.

In some embodiments, the movement optimisation module **304** is further configured for pre-fetching operations, wherein a container is moved closer to a station prior to it being required at the station. Containers are then ready to be dropped off when required, which may reduce the uncertainty of the drop off time.

In some embodiments, the system may be configured to plan the robot paths and establish robot path reservations sufficiently far in the future to allow the algorithms to complete.

In some embodiments, the degree of forward planning required may be computed by simulation.

The simulations may be used to adjudicate (in a statistical sense) between the efficiency gains of planning far into the future; against the efficiency loss of having higher probabilities of having to re-plan when robots fail to maintain their plan, because of various reasons, such as short-term communication packet losses, and/or robots running outside the allowed tolerances.

The product placement optimisation module **306** may be configured to determine a set of potentially advantageous locations to place a particular container containing particular items. The product placement optimisation module **306** may utilize relevant information, such as the layout of the grid, the frequency at which a particular item is requested, future ordering, predicted future ordering, the location of workstations, the location of charging stations, and the congestion level of particular areas and branches of the path, among others, in determining the set of potentially advantageous locations to place a particular container containing particular items.

A robot may be tasked with transporting one or more containers, each of which may contain one of more items, to satisfy the demands of one or more service pick stations. Each container may be provided with an index number related to a stack location so that particular containers may be biased towards particular stack locations.

The distribution of and positioning of a container within a stack or relative to the layout of a grid may contribute towards the overall operational efficiency of a warehouse.

There are various situations where a container needs to be placed somewhere in the facility and these situations present an opportunity to re-evaluate and/or optimise the distribution of the position of containers in the facility.

There are various considerations that would indicate that a position is better or worse than another position, which

may include, but are not limited to, distance to workstations, level of congestion in the area, which containers will be blocked by a particular container, logical groupings of containers relative to environmental factors (e.g. containers containing flammable objects may require special positioning), intelligent pre-fetching to a location by a work station.

These considerations may be utilized by the system to compare one position with another, for example, by using a weighted algorithm or any other suitable method.

For example, when a new container is introduced into the facility, when a container is returned to the facility, when one or more containers are moved by robots attempting to access the items stored deep within a stack, when items are placed in/removed from the container, when a container is marked damaged, when a container is marked as dirty, etc.

This optimisation can be conducted at various times, for example, in some embodiments, the optimisation is conducted to determine a new position for every container that has to be moved, such as those that have to be removed so that a particular container below can be accessed.

For example, the number of robot movements and operations may be potentially reduced if frequently ordered items and only a certain number of items for each given SKU# are distributed in the easiest to access areas of the warehouse (e.g. the closest locations to each pick station and/or the tops of stacks of containers).

An "active window" is defined as the number of orders' worth of containers to keep in the active state (on hand to service workstations) and determined by the system. The product placement optimisation module **306** may be configured to assign scores to containers, biasing the overall hive layout to tend towards a top layer of active containers, with reserve stock underneath.

This scoring system may be determined by the business rules module **310**, and set based upon information such as the stock expiry date. Historical orders may be utilized, among other information, to factor into calculating a score for containers, and this score may be updated on a continual basis every time the stock level of a SKU# changes. This scoring system may be utilized to help bias the positions of containers to maintain the optimality of positioning of containers within the facility.

In some embodiments, the system may be configured to control robot movement to maintain an "active" pool of one or more containers per SKU# to satisfy the demands of one or more service workstations. As an "active" pool becomes depleted, "reserve" containers may be promoted into the "active" pool.

In some embodiments of the system, the system may be configured to control robot movement using a "put-away algorithm" to determine a "best match" stack location from an available pool of empty locations when placing a container.

In some embodiments, the "active" pool may be configured to support parallel demand from the one or more service workstations.

In some embodiments, the product placement optimisation module **306** may also balance orders between the pick stations.

The robot physics model module **308** may be configured to store a set of variables that are designed to model the particular physical properties relevant to a robot. For example, the model may indicate physical characteristics such as the length, weight, height and width of a robot, the maximum carrying capacity of a robot, the rotational speed of the robot, the winch cycle time of a robot, the maximum velocity and acceleration of a robot, the ability for a robot to perform certain actions given a set amount of battery life, etc. The robot physics module **308** may interface with the business rules module **310** in determining limits on certain characteristics of robot movement, including the maximum velocity, maximum acceleration, and maximum rotational speed of a robot. For example, a robot carrying a number of cartons of eggs may be required to only accelerate/decelerate at 25% of the maximum acceleration/deceleration of the robot due to the vulnerability and fragility of the eggs due to physical forces.

The business rules module **310** develops and applies a set of business rules based upon the particular circumstances of the warehouse, robots and communications systems. For example, the business rules module **310** may provide that for certain classes of items, various restrictions are in force for the robot physics model module **308** to potentially reduce the amount of damage incurred by goods in transit. Examples of where business rules may be implemented include high risk products (e.g. acid, bleach etc.), containers with aerosols, and containers with flammable contents, among others. Empty containers may also be treated differently to other containers.

The business rules may include actions such as cleaning a container prior to re-use, slowing down robots containing certain objects, etc.

The business rules module **310** may also be configured to develop and apply sets of rules governing the placement of products. For example, different rules may be in place for high-frequency items, items that may be picked soon due to incoming orders, etc.

The clearance module **312** may be configured to store and provide clearances for various robots. A system of clearances may be accessed to determine whether a path is clear for a robot to traverse. The clearance module **312** may be implemented as a passive collision avoidance system, wherein robots are only given the smallest amount of work possible without impacting performance.

Upon providing a robot with a new instruction, the clearance module **312** checks that it will not be possible to collide with another robot, based upon, for example, grid dimensions, grid positions, move commands generated by planning, cancellation of move commands (generated on events such as a controlled stop), the current positions and speeds of robots, braking ability of robots as well as where they have been cleared to visit.

The clearance module **312** may be configured to issue clearance "just in time", and may be used to grant permissions to robots to continue along their planned paths. A new clearance may be generated (or withheld) in response to each robot status report. As such, the clearance module **312** may act as a path conflict resolver. Where clearances are required, the clearance module **312** may interact with the movement optimisation module **304** to dynamically re-plan routes to resolve or avoid conflicts.

The clearance module **312** may provide to the control interface **302** what the clearances for a path would be, notification of when a clearance is issued (e.g. to the planning system as this may allow dynamic re-planning from the end of the current clearance), notification of when a clearance is withheld (e.g. to identify error cases, and to identify needs to re-plan), and to an alerting system (because there is a potential problem with a robot, robot communications, or the control system **202**).

The clearance module **312** may be configured to devise clearance schemes based upon a set of tolerances, including missed messages, processing time, clock sync and robot discrepancies with the physics model, among others.

The clearance module **312** may provide a set of safe entry times for one or many position on the grid, based upon robot position and speed updates, and clearances given/withheld. The set of safe entry times may be dynamically updated as the conditions of the grid change.

The clearance module **312**, in some embodiments, may be configured such that robots are only provided clearances for a predetermined period of time (e.g. 3 seconds). The clearance given to a robot may be configured such that the period of time is sufficient for the robot to come to rest without risking a collision.

In some embodiments, the clearance module **312** may be configured such that clearances are provided such that the control system **202** may be able to miss a configurable number of status messages from the robot, and still have the robot continue operation for a short period of time. This design may result in a system that may be more tolerant to missed packets, which may be advantageous in having continued operation even where some issues with communications are encountered. The configurable number may be set such that there is a high probability that the control system **202** is likely to receive a status message from the robot before the robot autonomously decelerates to be at rest at the end of its clearance.

In some embodiments, if a robot has begun to decelerate, it will be allowed to come to rest and the control system **202** may then cancel its onward reservations and re-plans its path over the grid.

The reservation module **314** reserves various paths on the grid (e.g. robot A is planning to take path X and reserves path X during the expected traversal time. Robot B, knowing that robot A has reserved path X, chooses path Y instead). The reservation module **314** may be designed to create non-conflicting robot movement plans, and may be configured to work in conjunction with the clearance module **312** and the movement optimisation module **304**.

The reservation module **314** may be configured to provide reservations for a robot for a grid location for a span of time, where no two robots may be given overlapping reservations, taking into account tolerances for robots being marginally off plan, tolerances for lost robot communication messages, and tolerances for clock discrepancies, among others.

In some embodiments, the reservation module **314** is used to reserve routes in advance and to make sure that robots do not plan to take conflicting paths, especially where there are a large number of robot actions and tasks taking place simultaneously. The reservation module **314** may be configured to allow sufficient tolerance for any robot to stop under controlled braking without risking a collision.

The reservation module **314** may be configured to interact with the movement optimisation module **304** to establish the robot path reservations sufficiently far in the future to enable forward planning. In some embodiments, the reservation module **314** and the movement optimisation module **304** allow sufficient forward planning to complete the computation of the movement algorithms.

The command generation and scheduler module **316** generates a set of instructions to be transmitted to the one or more robots. These instructions may include, for example, that robot A is required to move to location B to obtain container C, bring container C to a workstation and then return container C to a particular location D. These instructions may be transmitted in a near-real time/real-time configuration, in a just-in-time configuration, and/or provided ahead of time to allow for planned/scheduled routes. Further, in some embodiments, the command generation and scheduler module **316** coordinates the reservations and clearances to help a robot expeditiously navigate its way across a facility.

The command generation and scheduler module **316** may be configured to provide a command set comprising a single path, or one or more paths, and/or a number of operations to be performed at various locations. The command generation and scheduler module **316** provides these commands to the robot communications module **318** to be provided to the individual robots. In some embodiments, the command generation and scheduler module **316** pre-populates instructions for a particular robot—these instructions may then be provided to the robot through the robot communications module **318** to be executed at a future time.

The robot communications module **318** may be configured to transmit information back and forth from the robots via the one or more base stations and the base station controller **206**. In some embodiments, the robot communications module **318** may communicate through the use of wireless signals. As indicated above, these instruction sets are not necessarily just-in-time, instruction sets may be sent for the coordination of future movements.

The robot communications module **318** may receive status reports from various robots. The robot communications module **318** may be implemented in various ways, such as utilizing synchronous, asynchronous, polling, push or pull methodologies. Further, various implementations may or may not include the use of communications "handshaking".

In some embodiments where there is no "handshaking", the communication systems may not guarantee message delivery, and lost packets may ensue. Potential advantages to such a system may include decreased bandwidth requirements and the submission of instructions on a best efforts basis. Various schemes may be implemented to minimize the impact of lost packets, such as timed rebroadcasting of instruction packets, sending overlapping instruction packets that contain parity information or other validation schemes, or other flow control and retransmission schemes.

In other embodiments of the invention, "handshaking" may be used to ensure that packets are received.

Commands to the robots may be issued ahead of the start time for an operation to be performed by a robot, and this time between the start time and the issuance of a command may be a configurable parameter.

In some embodiments, commands are repeated to the robots to ensure delivery, and the robots may provide acknowledgements that commands were received.

Where a message is not received before a scheduled start time, the robot may be configured to ignore the command and may return a status message indicating that the command was received too late. In this case, the robot control system **202** may be configured to cancel the existing reservations for the robot; and re-plan the tasking for the robot.

In some embodiments, the robot returns a regular status message that acknowledges the last command received (for example, by a command sequence number). The robot control system **202**, in some embodiments, may be configured such that no new command can be issued to a particular robot until the last command issued is acknowledged by the robot. If the command is not acknowledged by the robot after a particular period (e.g. a configurable a time-out period); the robot control system **202** may be configured to cancel the existing reservations for the robot. When (command) communication is re-established with the robot; the robot control system **202** re-plans the operation for the robot.

On receipt of each robot status message, the robot control system **202** may be configured to extend a robot's current movement clearance through the clearance module **312**.

The charge manager module **320** may be configured to develop a movement plan to recharge robots. The charge manager module **320** may be configured to estimate when robots will have a specified minimum charge, and ensure that all robots are able to charge at or before that point.

The alert/notification module **322** may be configured to provide an alert or notification to the control interface **302** when a potential issue has arisen, or based upon a predetermined business rule, e.g. a predetermined number of clearances have been withheld due to conflicts.

The present system and method may be practiced in various embodiments. A suitably configured computer device, and associated communications networks, devices, software and firmware may provide a platform for enabling one or more embodiments as described above. By way of example, FIG. **1** shows a generic computer device **100** that may include a central processing unit ("CPU") **102** connected to a storage unit **104** and to a random access memory **106**. The CPU **102** may process an operating system **101**, application program **103**, and data **123**. The operating system **101**, application program **103**, and data **123** may be stored in storage unit **104** and loaded into memory **106**, as may be required. The computer device **100** may further include a graphics processing unit (GPU) **122** which is operatively connected to the CPU **102** and to memory **106** to offload intensive image processing calculations from the CPU **102** and run these calculations in parallel with the CPU **102**. An operator **107** may interact with the computer device **100** using a video display **108** connected by a video interface **105**, and various input/output devices such as a keyboard **115**, mouse **112**, and disk drive or solid state drive **114** connected by an I/O interface **109**. In a known manner, the mouse **112** may be configured to control movement of a cursor in the video display **108**, and to operate various graphical user interface (GUI) controls appearing in the video display **108** with a mouse button. The disk drive or solid state drive **114** may be configured to accept computer readable media **116**. The computer device **100** may form part of a network via a network interface **111**, allowing the computer device **100** to communicate with other suitably configured data processing systems (not shown). One or more different types of sensors **135** may be used to receive input from various sources.

The present system and method may be practiced on virtually any manner of computer device including a desktop computer, laptop computer, tablet computer or wireless handheld. The present system and method may also be implemented as a computer-readable/useable medium that includes computer program code to enable one or more computer devices to implement each of the various process steps in a method in accordance with the present invention. In cases of more than one computer device performing the entire operation, the computer devices are networked to distribute the various steps of the operation. It is understood that the terms computer-readable medium or computer useable medium comprises one or more of any type of physical embodiment of the program code. In particular, the computer-readable/useable medium can comprise program code embodied on one or more portable storage articles of manufacture (e.g. an optical disc, a magnetic disk, a tape, etc.), on one or more data storage partitions of a computing device, such as memory associated with a computer and/or a storage system.

The mobile application of the present invention may be implemented as a web service, where the mobile device includes a link for accessing the web service, rather than a native application.

The functionality described may be implemented to any mobile platform, including the iOS™ platform, ANDROID™, WINDOWS™ or BLACKBERRY™.

It will be appreciated by those skilled in the art that other variations of the embodiments described herein may also be practiced without departing from the scope of the invention. Other modifications are therefore possible.

A number of different algorithms and techniques may be used in determining a preferential path for a robot to take, including, but not limited to: branch and bound algorithms, constraint programming, local search, heuristics, graph-traversal, dynamic path learning advisor techniques, pruning techniques and Bayesian graph searching techniques, Dijikstra's algorithm, Bellman-Ford algorithm, Floyd-Warshall algorithm, Johnson's algorithm, breadth-first recursive searches and depth-first recursive searches, weighted paths, A* search algorithm, variants on A* search algorithm (e.g. D*, Field D*, IDA*, Fringe, Fringe Saving A*, Generalized Adaptive A*, Lifelong Planning A*, Simplified Memory Bounded A*, Jump Point Search, Theta*).

In the sections below, sample search algorithms and heuristics are provided, according to some embodiments of the invention.

Sample Search Algorithm

In this section, a sample, simplified algorithm is provided, according to some embodiments of the invention.

For illustrative purposes, the algorithm is provided graphically as a workflow under FIG. **4**, according to some embodiments of the invention. It is to be understood that this sample algorithm is a non-limiting example that is solely provided as illustration to the concepts as described above.

The algorithm may be an iterative search algorithm that may utilize a branch & bound search and may apply a "near-best-first" heuristic model including a 'heat map' for congestion avoidance. Branches may be selected using a weighted cost function, and the algorithm may be loosely coupled to grid/robot shape/size.

In some embodiments, branches may be held in a sorted collection.

According to an embodiment of the algorithm, the following recursive branch and bound function is applied:

```
On each iteration:
    (a) Select lowest cost branch b,
    (b) Branch b in all directions to create new branches B
    (c) For each branch b' in B:
        If b' has reached target:
            return b'
        Else:
            Add b' to search
            Cost comparator allows tracking of lowest cost branch for
next iteration
```

In performing a path search, various heuristics may be applied to reduce the computations required, by, depending on the heuristic applied, removing entire branches or conducting a less computationally intensive analysis. Sample heuristic techniques are provided in a later section of this specification.

Where a new branch has a conflict with a path that another robot may be taking, or conflicts with an idle robot, the search algorithm may:

Alter the branch to outrun the conflicting reservation (if acceleration profile allows);

Alter the branch to contain a wait at any position along its path; or Discard the branch as infeasible

In some embodiments, paths may be selected where robots wait at their starting points.

In doing so, the search space can never truly be exhausted (e.g. if there are currently no acceptable paths for a robot to take to its destination, a path may be selected where the robot waits until a non-conflicting path is available).

Sample Heuristic Techniques

The search algorithm may be configured to preferentially balance any number of goals such as taking the shortest possible time, tending to avoid congested areas etc.

The following provides a simple, non-limiting example of the application of the use of heuristics for illustrative purposes.

In an embodiment of the invention, each search may track the current lowest cost branch and weighted cost functions may be used to bias the selection ordering of the branches based upon various heuristics, which may include: (a) a projected shortest path time and (b) a projected accumulated heat based on a heat-map. Other heuristic techniques may be contemplated but for illustrative purposes, further detail will be provided for the two identified above.

(a) Projected Shortest Path Time

For any branch, the control system may determine the shortest possible path time from the current branch tip to the destination.

The projected time cost may then be determined as the total time for the branch so far (including, for example, any waiting that was required, etc.) added to the time for the shortest possible unconstrained path to the target.

(b) Projected Minimum Heat (Based on a Heat Map)

In developing a heat-map, a 'heat' value may be assigned to each coordinate, approximating a model of congestion at points on the grid, or for particular areas of the grid.

FIG. **5** provides a sample heat map, according to some embodiments of the invention.

In some embodiments, the 'heat' value may be determined using proximity to workstations, but in other embodiments of the invention, the 'heat' may be observed/learned/calculated/predicted using a variety of other techniques, some of which may be dynamic or iterative techniques.

Similar to the projected shortest path, an unconstrained path may be projected to the destination.

The projected minimum heat may then be determined. In some embodiments, the projected heat cost is the sum of the heat of all visited coordinates in the current branch added to the heat of the 'coldest' (the least hot) of the projected paths.

Sample Weighted Cost Function

In some embodiments, the algorithms used are based upon weighted cost functions. Such algorithms may be amenable to optimisation of the associated cost coefficients by studying the results of large numbers of concurrent simulations in the cloud configured to use different coefficients, and/or applying various machine learning approaches and techniques, possibly using large sets of observed and/or simulated data.

In some embodiments, the search algorithm has two cost coefficients: (a) the projected shortest path time coefficient (C_t), and (b), the projected minimum heat coefficient (C_h).

In some embodiments, the search algorithm may include the following equation:

$$\text{Branch cost}=C_t*\text{PSP}+C_h*\text{PMH}$$

(Where PSP refers to projected shortest path time and PMH refers to projected minimum heat)

In some embodiments, the cost function may be utilized with configurable or machine-learning derived exponents that model complex relationships. A sample, simplified cost function, provided for illustrative purposes includes:

Branch cost=C_t*PSP^x+$C_{h*PMH}{}^Y$, where x & y may be further configurable and/or machine learned exponents.

FIG. **6***a* provides a table demonstrating how a search branch's projected cost could change as a result of using different coefficients in the path search algorithm. These coefficients could be derived using refinement by a machine learning technique according to some embodiments of the invention.

FIG. **6***b* illustrates how the use of different cost coefficients demonstrated in FIG. **6***a* changes which branch will be selected by the next iteration of the search algorithm.

In some embodiments, the control system **202** may be further configured to develop, adapt and apply a set of rules over time to refine a set of machine learned coefficients and/or exponents. The use of machine learned coefficients and/or exponents may potentially increase the effectiveness of the heuristic techniques over a duration of time.

Sample Shunting Search

The system may be configured to adjust robot paths to take into account the positions of idle robots. In some embodiments, there may be idle robots which may be tracked independently of robots with tasks. These idle robots may not have planned paths and associated reservations and may need to be considered separately.

A separate "shunt search" may be performed when a task is being finalised. The "shunt search" may be comprised of finding paths to move robots which are idle now, or will go idle in the path of the robot which is being tasked (hereinafter referred to as the primary robot), to locations where they may continue being idle and not be in the way of the path of the primary robot.

This "shunt search", in some embodiments, comprises performing a search where, for each robot which is idle now, or will go idle in the path of a primary robot, a search is performed which may be deemed solved upon finding a location in which it can remain indefinitely.

The "shunt search" may use the same branch & bound search algorithm as the primary robot path search, but may have different cost coefficients and solution criteria. If a robot is unable to move out of the way in time, a wait may be added to the start of the primary robot's path and the primary robot's path may be recalculated.

Sample Put-Away Algorithm

An algorithm may be used to determine a stack location for a container to be returned to. Containers may be returned for various reasons, and the location in which a container is returned to may be optimised for various advantages, such as improving the distribution of objects/containers in the hive.

Every stack location in the hive may be scored with a configurable, weighted cost function of:

Average distance (measured in robot operation time) from all workstations;

Distance (measured in robot operation time) from closest workstation; and

Approximate dig cost (if depth >0)

The system may keep a "Hive Plan" of the current end state of the hive after all operations in the plan have been executed.

The "Hive Plan" may also track the "available surface" in which a robot can place a container. Each container has an

index of its position in the totally ordered set of containers, as defined by the product placement optimisation module **306**.

Each stack location has an equivalent index in the totally ordered set of stack locations as defined by the weighted cost function.

These indices are remapped to the range 0-1 by dividing by the size of their respective sets, and the stack locations in the available surface are ranked by how closely their indices match that of the container's index.

The final selection is made via a weighted cost function of the difference between these indices and other factors such as how long the ideal path is from the source to the stack location and how long the stack is reserved for in the current plan.

Other business rules can be enforced at this stage, such as limiting the total weight of a stack; controlling the position of hazardous or special substances (e.g. aerosols and inflammable materials) etc.

Sample Return Scenario

The following provides a sample returns process that may be supported/controlled by the system. This process could be applied where an order is scratched, totes did not leave the hive, an order is returned by customer, or a delivery failed to a customer. Other situations may also be contemplated. A returned product (which may be in a container, other holding device such as a tote, etc.) can be processed at a workstation that provides reworking or rejection of the products.

The container/tote may be scanned so that the controller can position the storage bins it expects to need close to the workstation. Supply bins may be selected based on SKU and expiry date. Product items may be removed by the picker one-by-one and scanned. When the container arrives at the workstation, a picker (automated or manual) may be instructed/controlled to place the item into the container.

The picker may also be asked to confirm there are no further eaches of this SKU# left, before the container is released.

Products that are no longer suitable for return to stock may be picked into containers; which, at various times, such as when full, or at the end of the day, may be removed at the workstation and the contents sent to another area, such as the staff shop or disposal as appropriate.

While the disclosure has been provided and illustrated in connection with specific, presently-preferred embodiments, many variations and modifications may be made without departing from the spirit and scope of the invention(s) disclosed herein. The disclosure and invention(s) are therefore not to be limited to the exact components or details of methodology or construction set forth above. Except to the extent necessary or inherent in the processes themselves, no particular order to steps or stages of methods or processes described in this disclosure, including the Figures, is intended or implied. In many cases the order of process steps may be varied without changing the purpose, effect, or import of the methods described. The scope of the invention is to be defined solely by the appended claims, giving due consideration to the doctrine of equivalents and related doctrines.

The invention claimed is:

1. A system for controlling movement of transporting devices arranged to transport containers, the containers being stored in stacks arranged in a facility, the facility having pathways arranged in a grid-like structure above the stacks, the transporting devices being configured to operate on the grid-like structure, the system comprising:

a movement optimisation unit configured to determine a route of a transporting device from one location on a grid-like structure to another location on the grid-like structure for each transporting device;

a reservation unit configured to reserve a path on the grid-like structure for each transporting device based on the determined route, wherein the path reserved for each transporting device is provided such that no two transporting devices have locations on the grid-like structure which would cause transporting devices to overlap at a same time; and

a clearance unit configured to provide a clearance instruction for each transporting device to traverse a portion of the reserved path,

wherein the clearance instruction is provided for execution by a control unit on each transporting device at a future time.

2. The system according to claim **1**, wherein the time between the time the clearance instruction is provided and the future time is a configurable parameter.

3. The system according to claim **1**, wherein the clearance unit is further configured such that the clearance instruction is not provided until a last issued clearance instruction is acknowledged by a transporting device.

4. The system according to claim **1**, wherein the clearance unit is further configured for each transporting device, to cancel an existing reserved path when the last issued clearance instruction is not acknowledged by a transporting device within a predetermined period of time.

5. The system according to claim **4**, wherein the system is further configured to re-plan an operation for the transporting device when communication is re-established with the transporting device.

6. The system according to claim **1**, wherein the clearance unit is configured to grant or withhold providing the clearance instruction for a transporting device to traverse a portion of the reserved path in response to a status report received from each transporting device.

7. The system according to claim **1**, wherein the clearance unit is configured as a passive collision avoidance system, wherein each transporting device is operated in a manner without impacting system performance.

8. The system according to claim **1**, wherein the clearance unit is configured to grant or withhold providing the clearance instruction for a transporting device to traverse a portion of the reserved path based on at least one of:

dimensions of the grid-like structure, positions on the grid-like structure, commands to move the transporting device, cancellation of commands to move the transporting device, a current position of the transporting device, a speed of the transporting device, a braking ability of the transporting device, and the clearance instructions provided to the transporting device.

9. The system according to claim **1**, wherein at least one of the clearance unit, and the movement optimisation unit is configured to dynamically re-plan a route of at least one transporting device.

10. The system according to claim **1**, when at least one message is not received by the system from the transporting device, the movement optimisation unit is configured to calculate a route for a transporting device that traverses a portion of the reserved path to resolve or avoid conflicts.

11. The system according to claim **1**, wherein the clearance unit is configured to provide the clearance instruction based upon a set of tolerances, including at least one of: missed messages, a processing time, a clock sync, and transporting device discrepancies with a physics model.

12. The system according to claim **1**, wherein the clearance unit is configured to calculate a set of safe entry times for at least one position on the grid-like structure based upon at least one of transporting device position, speed updates, and the clearance instructions given and withheld.

13. The system according to claim **1**, wherein the clearance unit is configured to provide the clearance instructions for a predetermined period of time.

14. The system according to claim **1**, comprising:

a control unit configured to control movement of the transporting devices,

wherein the clearance unit is configured to provide to the control unit at least one of: the clearance instructions required to traverse a reserved path, notification of when the clearance instruction is issued, notification of when the clearance instruction is withheld, and problems with a transporting device,

wherein the control unit is configured to control movements of the transporting devices based on the information received from the clearance unit.

15. A storage system comprising:

a facility arranged to store containers in a plurality of stacks, the facility comprising a plurality of pathways arranged in a grid-like structure above the stacks;

transporting devices arranged to transport containers and arranged to operate on the grid-like structure; and

the system according to claim **1**.

16. The storage system according to claim **15**, wherein each transporting device has a footprint of a single grid position on the grid-like structure.

17. The storage system according to claim **15**, wherein each transporting device is configured to ignore a received clearance instruction when the clearance instruction is not received before a scheduled start time.

18. The storage system according to claim **15**, wherein the transporting device is further configured to return a status message indicating that the clearance instruction was received too late when the clearance instruction is not received before a scheduled start time.

19. The storage system according to claim **18**, wherein the system is further configured to cancel an existing reserved path for a transporting device and to re-plan tasking for the transporting device when the clearance instruction was received too late by the transporting device.

20. A method for controlling movement of transporting devices arranged to transport containers, the containers being stored in stacks arranged in a facility, the facility having pathways arranged in a grid-like structure above the stacks, the transporting devices configured to operate on the grid-like structure, the method comprising:

determining a route from one location on the grid-like structure to another location on the grid-like structure for each transporting device;

reserving a path on the grid-like structure for each of the transporting devices based on the determined route, wherein the path reserved for each transporting device is provided such that no two transporting devices have locations on the grid-like structure which would cause transporting devices to overlap at a same time; and

providing a clearance instruction for each transporting device to traverse a portion of the reserved path, wherein the clearance instruction is provided for execution by each transporting device at a future time.

* * * * *

APPENDIX D

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Patent Application of	)	**MAIL STOP AMENDMENT**
Robert STADIE, et al.	)	Group Art Unit: 3651
Application No.: 15/992,899	)	Examiner: Thomas Randazzo
Filed: May 30, 2018	)	Confirmation No.: 1341
For: METHODS, SYSTEMS AND APPARATUS FOR CONTROLLING MOVEMENT OF TRANSPORTING DEVICES	)	

AMENDMENT AND REPLY

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Commissioner:

In response to the Office Action dated September 6, 2018, please consider the following remarks for the above-identified patent application:

REMARKS

This communication is a full and timely response to the non-final Office Action dated September 6, 2018. Claims 1-15 are currently pending. The claims are maintained as-is. No new matter is added.

Preliminary Matters

Applicant thanks the Examiner for considering all the references cited in the Information Disclosure Statement of May 30, 2018, and for accepting the drawings. Applicant thanks the Examiner for acknowledging claim to foreign priority under 35 U.S.C. §119.

Brief overview of the application

Before turning to the art rejections of the claims, a brief overview of this application is provided to facilitate an understanding of the subject matter at issue. The claims are not limited, however, by this overview discussion.

The present application relates to a system (and method) for controlling movement of transporting devices arranged to transport containers. In an exemplary embodiment, the system can include three units that are used to respectively determine, reserve, and utilize a route on a grid-like structure.

In an exemplary embodiment, a movement optimization unit can be used to determine a route from one location to another location. According to the present specification on page 21, lines 22 – 23, pre-processing of potential routes may be performed to determine, initially, potential routes from one location to another location. Due to the use of pre-processing, the routes determined can be time-independent, not taking into account the current movements of

transporting devices on the grid-like structure. The routes determined, therefore, in some cases are not suitable for immediate use due to the potential for collisions between transporting devices.

In an exemplary embodiment, a reservation unit can be used to convert the time-independent routes into ones more suitable for utilization. As described on page 27, line 28 – page 28, line 6 of the present description, the reservation unit can reserve a route determined by the movement optimization units. In this context, reserving a route can mean preventing other transporting devices from traversing a part of a route when that part of a route is expected to be traversed by the transporting device for which the route is reserved. In this way, the reservation unit can create a non-conflicting transporting device movement plans with no two transporting device being given overlapping reservations.

The use of a movement optimization unit and a reservation unit, in an exemplary embodiment, may not result in perfect routes suitable for traversal by the transporting device because transporting devices may be marginally off route due to tolerances in the transmission of communication messages and tolerances for clock discrepancies (page 28, lines 4 – 6). Accordingly, a clearance unit can be used to issue "just in time" permissions for a transporting device to continue along a planned route once the tolerances have been sufficiently resolved. In this way, the clearance unit can operate as a path conflict resolver (page 26, lines 24 – 27 of the present description).

As a result of the previously described units, successful traversal by transporting devices of routes on a grid-like structure can be achieved. In particular, such a system can be useful for deterministic grid-like structures in which the location of each transporting device (within a

tolerance) can be known and whose position after a given time interval can also be known (to within a tolerance) due to knowledge of the velocity, and future velocity, of the transporting device. Use of the three previously described units minimizes collisions between transporting devices because the routes can be reserved to avoid collisions and any small tolerances can be accounted for using clearances. Therefore transporting devices may be used at higher speeds with smaller gaps between them.

Claim Rejections under 35 U.S.C. § 103

Claims 1-11 and 14-15 are rejected under 35 U.S.C. § 103 as allegedly being unpatentable over Kunzig et al (US Patent No. 8,381,982) in view of Hognaland (US Patent Application Publication No. 2016/027421).

Claims 12 and 13 are rejected under 35 U.S.C. 103 as allegedly being unpatentable over Hognaland in view of Kunzig et al.

Applicant traverses because Kunzig's system is fundamentally different from the claimed features.

Applicant submits that Kunzig's system does not both pre-process routes using a movement optimization unit and reserve routes for use using a reservation unit because the system disclosed in Kunzig is not deterministic. More specifically, column 7, lines 39 – 42 of Kunzig make it clear that Kunzig uses both automated vehicles and manned vehicles. The manned vehicles do not behave deterministically because they are controlled by humans who do not act deterministically. In particular, the centralized computer of Kunzig arranged to control the automated vehicles may know the current position of the automated vehicles and the

expected future velocities of such automated vehicles. However, the computer cannot know the expected future velocities of the manned vehicles due to the human based control which does not act deterministically nor report back to the computer expected (or unexpected) changes in velocity and when they will occur.

Moreover, a human when beginning to traverse a route will not know the locations of other manned vehicles or automated vehicles at particular points of route when the manned vehicle reaches those points and therefore does not know how they will react when they reach the particular points on the route. Therefore, Kunzig fails to disclose or suggest a reservation unit that is configured to reserve non-conflicting routes for transporting devices. Instead, Kunzig discloses in column 5, lines 37 – 38, column 6, lines 44 – 46 and column 7, lines 31 – 32, that a desired route is determined for each automated vehicle. That is, Kunzig merely discloses the determination of an ideal route (e.g. a straight line route) without accounting for the movements of other vehicles. However, these routes in Kunzig are not reserved for each transporting devices such that "no two transporting devices have locations … which would cause transporting devices to overlap at a same time" as recited in the independent claim 1.

Kunzig employs a more traditional collision avoidance strategy since no determined route has been reserved to avoid any other vehicle. In particular, Kunzig relies on "a predicted trajectory and a safety zone for each manned vehicle and each automated vehicle" (column 7, lines 35 – 42) whereby an intersection of the safety zone of each manned vehicle and each automated vehicle are used to predict a potential collision and avoidance taken. This has the disadvantage that transporting devices must be spaced apart enough to permit the avoidance action to be taken and must run at a speed suitable for the avoidance action to have enough time

to take effect. This increases the number of slowdowns, turns or stops of the vehicles being required because collision avoidance is implemented only as the vehicle is traversing a route, not in the route reserved before traversing a route like in the claimed features.

Accordingly, Kunzig fails to disclose or suggest at least the reservation unit recited in the independent claim 1. Hognaland, alone or in combination with Kunzig, fails to disclose or suggest all the features of independent claim 1.

For foregoing reasons, Applicant submits independent claim 1 is patentable over the cited references. Independent claim 14 recites similar features as claim 1, therefore, is patentable for similar reasons as previously set forth. Dependent claims are patentable due to their dependencies and because of additional features recited therein.

Thus, favorable reconsideration of this application is respectfully requested in view of the foregoing amendments and remarks.

Conclusion

Should any questions arise about this application or should the Examiner believe that a telephone conference with the undersigned would be helpful in resolving any remaining issues pertaining to this application the undersigned respectfully requests that he be contacted at the number indicated below.

If additional fees are required for any reason, please charge Deposit Account No. 02-4800 the necessary amount.

Respectfully submitted,

BUCHANAN INGERSOLL & ROONEY PC

Date: December 3, 2018 By /Anand Mohan/

Patrick C. Keane
Registration No. 32,858

Anand Mohan
Registration No. 76,518

Customer No. 21839
703 836 6620

APPENDIX E

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

NOTICE OF ALLOWANCE AND FEE(S) DUE

20995 7590 11/27/2020
KNOBBE MARTENS OLSON & BEAR LLP
2040 MAIN STREET
FOURTEENTH FLOOR
IRVINE, CA 92614

EXAMINER	
RANDAZZO, THOMAS	
ART UNIT	PAPER NUMBER
3651	

DATE MAILED: 11/27/2020

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
16/575,906	09/19/2019	Robert STADIE	OCADO.013C1	7260

TITLE OF INVENTION: METHODS, SYSTEMS AND APPARATUS FOR CONTROLLING MOVEMENT OF TRANSPORTING DEVICES

APPLN. TYPE	ENTITY STATUS	ISSUE FEE DUE	PUBLICATION FEE DUE	PREV. PAID ISSUE FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	UNDISCOUNTED	$1200	$0.00	$0.00	$1200	03/01/2021

THE APPLICATION IDENTIFIED ABOVE HAS BEEN EXAMINED AND IS ALLOWED FOR ISSUANCE AS A PATENT. PROSECUTION ON THE MERITS IS CLOSED. THIS NOTICE OF ALLOWANCE IS NOT A GRANT OF PATENT RIGHTS. THIS APPLICATION IS SUBJECT TO WITHDRAWAL FROM ISSUE AT THE INITIATIVE OF THE OFFICE OR UPON PETITION BY THE APPLICANT. SEE 37 CFR 1.313 AND MPEP 1308.

THE ISSUE FEE AND PUBLICATION FEE (IF REQUIRED) MUST BE PAID WITHIN THREE MONTHS FROM THE MAILING DATE OF THIS NOTICE OR THIS APPLICATION SHALL BE REGARDED AS ABANDONED. THIS STATUTORY PERIOD CANNOT BE EXTENDED. SEE 35 U.S.C. 151. THE ISSUE FEE DUE INDICATED ABOVE DOES NOT REFLECT A CREDIT FOR ANY PREVIOUSLY PAID ISSUE FEE IN THIS APPLICATION. IF AN ISSUE FEE HAS PREVIOUSLY BEEN PAID IN THIS APPLICATION (AS SHOWN ABOVE), THE RETURN OF PART B OF THIS FORM WILL BE CONSIDERED A REQUEST TO REAPPLY THE PREVIOUSLY PAID ISSUE FEE TOWARD THE ISSUE FEE NOW DUE.

HOW TO REPLY TO THIS NOTICE:

I. Review the ENTITY STATUS shown above. If the ENTITY STATUS is shown as SMALL or MICRO, verify whether entitlement to that entity status still applies.

If the ENTITY STATUS is the same as shown above, pay the TOTAL FEE(S) DUE shown above.

If the ENTITY STATUS is changed from that shown above, on PART B - FEE(S) TRANSMITTAL, complete section number 5 titled "Change in Entity Status (from status indicated above)".

For purposes of this notice, small entity fees are 1/2 the amount of undiscounted fees, and micro entity fees are 1/2 the amount of small entity fees.

II. PART B - FEE(S) TRANSMITTAL, or its equivalent, must be completed and returned to the United States Patent and Trademark Office (USPTO) with your ISSUE FEE and PUBLICATION FEE (if required). If you are charging the fee(s) to your deposit account, section "4b" of Part B - Fee(s) Transmittal should be completed and an extra copy of the form should be submitted. If an equivalent of Part B is filed, a request to reapply a previously paid issue fee must be clearly made, and delays in processing may occur due to the difficulty in recognizing the paper as an equivalent of Part B.

III. All communications regarding this application must give the application number. Please direct all communications prior to issuance to Mail Stop ISSUE FEE unless advised to the contrary.

IMPORTANT REMINDER: Maintenance fees are due in utility patents issuing on applications filed on or after Dec. 12, 1980. It is patentee's responsibility to ensure timely payment of maintenance fees when due. More information is available at www.uspto.gov/PatentMaintenanceFees.

PART B - FEE(S) TRANSMITTAL

Complete and send this form, together with applicable fee(s), by mail or fax, or via EFS-Web.

By mail, send to: Mail Stop ISSUE FEE
Commissioner for Patents
P.O. Box 1450
Alexandria, Virginia 22313-1450

By fax, send to: (571)-273-2885

INSTRUCTIONS: This form should be used for transmitting the ISSUE FEE and PUBLICATION FEE (if required). Blocks 1 through 5 should be completed where appropriate. All further correspondence including the Patent, advance orders and notification of maintenance fees will be mailed to the current correspondence address as indicated unless corrected below or directed otherwise in Block 1, by (a) specifying a new correspondence address; and/or (b) indicating a separate "FEE ADDRESS" for maintenance fee notifications.

CURRENT CORRESPONDENCE ADDRESS (Note: Use Block 1 for any change of address)

20995 7590 11/27/2020

KNOBBE MARTENS OLSON & BEAR LLP
2040 MAIN STREET
FOURTEENTH FLOOR
IRVINE, CA 92614

Note: A certificate of mailing can only be used for domestic mailings of the Fee(s) Transmittal. This certificate cannot be used for any other accompanying papers. Each additional paper, such as an assignment or formal drawing, must have its own certificate of mailing or transmission.

Certificate of Mailing or Transmission

I hereby certify that this Fee(s) Transmittal is being deposited with the United States Postal Service with sufficient postage for first class mail in an envelope addressed to the Mail Stop ISSUE FEE address above, or being transmitted to the USPTO via EFS-Web or by facsimile to (571) 273-2885, on the date below.

(Typed or printed name)
(Signature)
(Date)

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
16/575,906	09/19/2019	Robert STADIE	OCADO.013C1	7260

TITLE OF INVENTION: METHODS, SYSTEMS AND APPARATUS FOR CONTROLLING MOVEMENT OF TRANSPORTING DEVICES

APPLN. TYPE	ENTITY STATUS	ISSUE FEE DUE	PUBLICATION FEE DUE	PREV. PAID ISSUE FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	UNDISCOUNTED	$1200	$0.00	$0.00	$1200	03/01/2021

EXAMINER	ART UNIT	CLASS-SUBCLASS
RANDAZZO, THOMAS	3651	700-214000

1. Change of correspondence address or indication of "Fee Address" (37 CFR 1.363).

❑ Change of correspondence address (or Change of Correspondence Address form PTO/SB/122) attached.

❑ "Fee Address" indication (or "Fee Address" Indication form PTO/SB/47; Rev 03-09 or more recent) attached. **Use of a Customer Number is required.**

2. For printing on the patent front page, list
(1) The names of up to 3 registered patent attorneys or agents OR, alternatively,
(2) The name of a single firm (having as a member a registered attorney or agent) and the names of up to 2 registered patent attorneys or agents. If no name is listed, no name will be printed.

1 ____________________
2 ____________________
3 ____________________

3. ASSIGNEE NAME AND RESIDENCE DATA TO BE PRINTED ON THE PATENT (print or type)

PLEASE NOTE: Unless an assignee is identified below, no assignee data will appear on the patent. If an assignee is identified below, the document must have been previously recorded, or filed for recordation, as set forth in 37 CFR 3.11 and 37 CFR 3.81(a). Completion of this form is NOT a substitute for filing an assignment.

(A) NAME OF ASSIGNEE

(B) RESIDENCE: (CITY and STATE OR COUNTRY)

Please check the appropriate assignee category or categories (will not be printed on the patent) : ❑ Individual ❑ Corporation or other private group entity ❑ Government

4a. Fees submitted: ❑Issue Fee ❑Publication Fee (if required) ❑Advance Order - # of Copies ____________

4b. Method of Payment: *(Please first reapply any previously paid fee shown above)*

❑ Electronic Payment via EFS-Web ❑ Enclosed check ❑ Non-electronic payment by credit card (Attach form PTO-2038)

❑ The Director is hereby authorized to charge the required fee(s), any deficiency, or credit any overpayment to Deposit Account No. __________

5. **Change in Entity Status** (from status indicated above)

❑ Applicant certifying micro entity status. See 37 CFR 1.29

❑ Applicant asserting small entity status. See 37 CFR 1.27

❑ Applicant changing to regular undiscounted fee status.

NOTE: Absent a valid certification of Micro Entity Status (see forms PTO/SB/15A and 15B), issue fee payment in the micro entity amount will not be accepted at the risk of application abandonment.
NOTE: If the application was previously under micro entity status, checking this box will be taken to be a notification of loss of entitlement to micro entity status.
NOTE: Checking this box will be taken to be a notification of loss of entitlement to small or micro entity status, as applicable.

NOTE: This form must be signed in accordance with 37 CFR 1.31 and 1.33. See 37 CFR 1.4 for signature requirements and certifications.

Authorized Signature ______________________ Date ______________________

Typed or printed name ______________________ Registration No. ______________________

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
16/575,906	09/19/2019	Robert STADIE	OCADO.013C1	7260

20995 7590 11/27/2020

KNOBBE MARTENS OLSON & BEAR LLP
2040 MAIN STREET
FOURTEENTH FLOOR
IRVINE, CA 92614

EXAMINER	
RANDAZZO, THOMAS	
ART UNIT	PAPER NUMBER
3651	

DATE MAILED: 11/27/2020

Determination of Patent Term Adjustment under 35 U.S.C. 154 (b)
(Applications filed on or after May 29, 2000)

The Office has discontinued providing a Patent Term Adjustment (PTA) calculation with the Notice of Allowance.

Section 1(h)(2) of the AIA Technical Corrections Act amended 35 U.S.C. 154(b)(3)(B)(i) to eliminate the requirement that the Office provide a patent term adjustment determination with the notice of allowance. See Revisions to Patent Term Adjustment, 78 Fed. Reg. 19416, 19417 (Apr. 1, 2013). Therefore, the Office is no longer providing an initial patent term adjustment determination with the notice of allowance. The Office will continue to provide a patent term adjustment determination with the Issue Notification Letter that is mailed to applicant approximately three weeks prior to the issue date of the patent, and will include the patent term adjustment on the patent. Any request for reconsideration of the patent term adjustment determination (or reinstatement of patent term adjustment) should follow the process outlined in 37 CFR 1.705.

Any questions regarding the Patent Term Extension or Adjustment determination should be directed to the Office of Patent Legal Administration at (571)-272-7702. Questions relating to issue and publication fee payments should be directed to the Customer Service Center of the Office of Patent Publication at 1-(888)-786-0101 or (571)-272-4200.

OMB Clearance and PRA Burden Statement for PTOL-85 Part B

The Paperwork Reduction Act (PRA) of 1995 requires Federal agencies to obtain Office of Management and Budget approval before requesting most types of information from the public. When OMB approves an agency request to collect information from the public, OMB (i) provides a valid OMB Control Number and expiration date for the agency to display on the instrument that will be used to collect the information and (ii) requires the agency to inform the public about the OMB Control Number's legal significance in accordance with 5 CFR 1320.5(b).

The information collected by PTOL-85 Part B is required by 37 CFR 1.311. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 30 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, Virginia 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, Virginia 22313-1450. Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether disclosure of these records is required by the Freedom of Information Act.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

Notice of Allowability	**Application No.** 16/575,906	**Applicant(s)** STADIE et al.	
	Examiner THOMAS RANDAZZO	**Art Unit** 3651	**AIA (FITF) Status** Yes

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address--

All claims being allowable, PROSECUTION ON THE MERITS IS (OR REMAINS) CLOSED in this application. If not included herewith (or previously mailed), a Notice of Allowance (PTOL-85) or other appropriate communication will be mailed in due course. **THIS NOTICE OF ALLOWABILITY IS NOT A GRANT OF PATENT RIGHTS.** This application is subject to withdrawal from issue at the initiative of the Office or upon petition by the applicant. See 37 CFR 1.313 and MPEP 1308.

1.☑ This communication is responsive to documents filed 9/16/2020.

☐ A declaration(s)/affidavit(s) under **37 CFR 1.130(b)** was/were filed on ______.

2.☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on ______; the restriction requirement and election have been incorporated into this action.

3.☑ The allowed claim(s) is/are 1-20 . As a result of the allowed claim(s), you may be eligible to benefit from the **Patent Prosecution Highway** program at a participating intellectual property office for the corresponding application. For more information, please see **http://www.uspto.gov/patents/init_events/pph/index.jsp** or send an inquiry to **PPHfeedback@uspto.gov.**

4.☑ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

Certified copies:

a) ☑All b) ☐ Some *c) ☐ None of the:

1. ☐ Certified copies of the priority documents have been received.
2. ☑ Certified copies of the priority documents have been received in Application No. 15/316,249 .
3. ☐ Copies of the certified copies of the priority documents have been received in this national stage application from the International Bureau (PCT Rule 17.2(a)).

* Certified copies not received: ______ .

Applicant has THREE MONTHS FROM THE "MAILING DATE" of this communication to file a reply complying with the requirements noted below. Failure to timely comply will result in ABANDONMENT of this application.
THIS THREE-MONTH PERIOD IS NOT EXTENDABLE.

5.☐ CORRECTED DRAWINGS (as "replacement sheets") must be submitted.

☐ including changes required by the attached Examiner's Amendment / Comment or in the Office action of Paper No./Mail Date ______ .

Identifying indicia such as the application number (see 37 CFR 1.84(c)) should be written on the drawings in the front (not the back) of each sheet. Replacement sheet(s) should be labeled as such in the header according to 37 CFR 1.121(d).

6.☐ DEPOSIT OF and/or INFORMATION about the deposit of BIOLOGICAL MATERIAL must be submitted. Note the attached Examiner's comment regarding REQUIREMENT FOR THE DEPOSIT OF BIOLOGICAL MATERIAL.

Attachment(s)

1.☑ Notice of References Cited (PTO-892)
2.☑ Information Disclosure Statements (PTO/SB/08), Paper No./Mail Date ______.
3.☐ Examiner's Comment Regarding Requirement for Deposit of Biological Material ______.
4.☑ Interview Summary (PTO-413), Paper No./Mail Date. 20201105.
5. ☑ Examiner's Amendment/Comment
6. ☑ Examiner's Statement of Reasons for Allowance
7. ☑ Other Four Foreign Refs attached.

/THOMAS RANDAZZO/
Primary Examiner, Art Unit 3651

Examiner's Amendment: This Examiner's Amendment is being made to advance issuance of a Notice of Allowance by correcting inadvertent oversight errors that would result in 112(b) rejections in Claims 1, 3, 4, 6 , 8, 11-14, 18, and 19 following the claim amendments made on 9/16/2020. Claims 1, 2, and 17 were amended to change "clearance" to "clearance instruction". However, limitations in Claims 1, 3, 4, 6, 8, 11-14, 18, and 19 should have also been amended to change "clearance instruction" to one of "a clearance instruction" or "the clearance instruction" as the context of each claim limitation requires. Therefore, by this Examiner's Amendment, Claims 1, 3, 4, 6, 8, 11-14, 18, and 19 shall now read as follows:

1. A system for controlling movement of transporting devices arranged to transport containers, the containers being stored in stacks arranged in a facility, the facility having pathways arranged in a grid-like structure above the stacks, the transporting devices being configured to operate on the grid-like structure, the system comprising:
a movement optimisation unit configured to determine a route of a transporting device from one location on a grid-like structure to another location on the grid-like structure for each transporting device;
a reservation unit configured to reserve a path on the grid-like structure for each transporting device based on the determined route, wherein the path reserved for each transporting device is provided such that no two transporting devices have locations on the grid-like structure which would cause transporting devices to overlap at a same time; and
a clearance unit configured to provide a clearance instruction for each transporting device to traverse a portion of the reserved path,
wherein the clearance instruction is provided for execution by a control unit on each transporting device at a future time.
3. The system according to Claim 1, wherein the clearance unit is further configured such that the clearance instruction is not provided until a last issued clearance instruction is acknowledged by a transporting device.
4. The system according to Claim 1, wherein the clearance unit is further configured for each transporting device, to cancel an existing reserved path when the last issued clearance instruction is not acknowledged by a transporting device within a predetermined period of time.
6. The system according to Claim 1, wherein the clearance unit is configured to grant or withhold providing the clearance instruction for a transporting device to traverse a portion of the reserved path in response to a status report received from each transporting device.
8. The system according to Claim 1, wherein the clearance unit is configured to grant or withhold providing the clearance instruction for a transporting device to traverse a portion of the reserved path based on at least one of:
dimensions of the grid-like structure, positions on the grid-like structure, commands to move the transporting device, cancellation of commands to move the transporting device, a current position of the transporting device, a speed of the transporting device, a braking ability of the transporting device, and the clearance instructions provided to the transporting device.
11. The system according to Claim 1, wherein the clearance unit is configured to provide the clearance instruction based upon a set of tolerances, including at least one of:
missed messages, a processing time, a clock sync, and transporting device discrepancies with a physics model.
12. The system according to Claim 1, wherein the clearance unit is configured to calculate a set of safe entry times for at least one position on the grid-like structure based upon at least one of transporting device position, speed updates, and the clearance instructions given and withheld.
13. The system according to Claim 1, wherein the clearance unit is configured to provide the clearance instructions for a predetermined period of time.
14. The system according to Claim 1, comprising:
a control unit configured to control movement of the transporting devices,
wherein the clearance unit is configured to provide to the control unit at least one of:
the clearance instructions required to traverse a reserved path, notification of when the clearance instruction is issued, notification of when the clearance instruction is withheld, and problems with a transporting device,
wherein the control unit is configured to control movements of the transporting devices based on the information received from the clearance unit.

18. The storage system according to Claim 15, wherein the transporting device is further configured to return a status message indicating that the clearance instruction was received too late when the clearance instruction is not received before a scheduled start time.
19. The storage system according to Claim 18, wherein the system is further configured to cancel an existing reserved path for a transporting device and to re-plan tasking for the transporting device when the clearance instruction was received too late by the transporting device.

Notice of Pre-AIA or AIA Status

1. The present application, filed on or after March 16, 2013, is being examined under the first inventor to file provisions of the AIA.

Allowable Subject Matter

2. **Claims 1-20** are allowed.

3. The following is an examiner's statement of reasons for allowance: With respect to claims 1, 2, 17, 18, and 20, the Applicant's Amendments (See Amendments, pages 2-6, dated 9/16/2020 were persuasive and overcome the 35 U.S.C. 112(b) rejections.

Independent **Claim 1** recites limitations that include a system for controlling movement of transporting devices arranged to transport containers, the containers being stored in stacks arranged in a facility, the facility having pathways arranged in a grid-like structure above the stacks, the transporting devices being configured to operate on the grid-like structure, the system comprising:

a movement optimisation unit configured to determine a route of a transporting device from one location on a grid-like structure to another location on the grid-like structure for each transporting device;

a reservation unit configured to reserve a path on the grid-like structure for each transporting device based on the determined route, wherein the path reserved for each transporting device is provided such that no two transporting devices have locations on the grid-like structure which would cause transporting devices to overlap at a same time; and

a clearance unit configured to provide a clearance instruction for each transporting device to traverse a portion of the reserved path,

wherein the clearance instruction is provided for execution by a control unit on each transporting device at a future time. These limitations, alone and in combination with the other

limitations in the independent and dependent claims, were neither found, nor taught or fairly suggested, in the prior art of record.

Independent **Claim 15** recites limitations that include a storage system comprising:

a facility arranged to store containers in a plurality of stacks, the facility comprising a plurality of pathways arranged in a grid-like structure above the stacks;

transporting devices arranged to transport containers and arranged to operate on the grid-like structure; and

the system according to Claim 1. These limitations, alone and in combination with the other limitations in the independent and dependent claims, were neither found, nor taught or fairly suggested, in the prior art of record.

Independent **Claim 21** recites limitations that include a method for controlling movement of transporting devices arranged to transport containers, the containers being stored in stacks arranged in a facility, the facility having pathways arranged in a grid-like structure above the stacks, the transporting devices configured to operate on the grid-like structure, the method comprising:

determining a route from one location on the grid-like structure to another location on the grid-like structure for each transporting device;

reserving a path on the grid-like structure for each of the transporting devices based on the determined route, wherein the path reserved for each transporting device is provided such that no two transporting devices have locations on the grid-like structure which would cause transporting devices to overlap at a same time; and

providing a clearance instruction for each transporting device to traverse a portion of the reserved path,

wherein the clearance instruction is provided for execution by each transporting device at a future time. These limitations, alone and in combination with the other limitations in the independent and dependent claims, were neither found, nor taught or fairly suggested, in the prior art of record.

Any comments considered necessary by applicant must be submitted no later than the payment of the issue fee and, to avoid processing delays, should preferably accompany the issue fee. Such submissions should be clearly labeled "**Comments on Statement of Reasons for Allowance**."

4. The prior art made of record and not relied upon is considered pertinent to Applicant's disclosure.

Any inquiry concerning this communication or earlier communications from the examiner should be directed to Thomas Randazzo whose telephone number is 313-446-4903. The examiner can normally be reached between 9:00am to 4:00pm EST Monday through Friday.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Gene Crawford, can be reached on 571-272-6911. The fax phone number for the organization where this application or proceeding is assigned is 571-273-8300.

Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://portal.uspto.gov/external/portal. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free).

/THOMAS RANDAZZO/
Primary Examiner, Art Unit 3651
November 5, 2020